

NASA
TT
F-623
c.1

G.T. Afanas'ev and V.K. Bobolev

INITIATION OF SOLID EXPLOSIVES BY IMPACT

**LOAN COPY: RETURN
AFWL (DOGL)
KIRTLAND AFB, N.**

0069215



TECH LIBRARY KAFB, NM

TRANSLATED FROM RUSSIAN



Published for the National Aeronautics and Space Administration
and the National Science Foundation, Washington, D.C.
by the Israel Program for Scientific Translations



AKADEMIYA NAUK SSSR
INSTITUT KHIMICHESKOI FIZIKI
Academy of Sciences of the USSR
Institute of Chemical Physics

G. T. Afanas'ev and V. K. Bobolev

INITIATION OF SOLID EXPLOSIVES BY IMPACT

(Initsirovanie tverdykh vzryvchatykh veshchestv udarom)

Izdatel'stvo "Nauka"
Moskva 1968

Translated from Russian

Israel Program for Scientific Translations
Jerusalem 1971

TT 70-50074
NASA TT F-623

Published Pursuant to an Agreement with
THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
and
THE NATIONAL SCIENCE FOUNDATION, WASHINGTON, D. C.

Copyright © 1971
Israel Program for Scientific Translations
IPST Cat. No. 5766
UDC 54.427.6 (621.8.031.4)

Translated by I. Shechtman
Edited by P. Greenberg

Printed in Jerusalem by Keter Press
Binding: Wiener Bindery Ltd., Jerusalem

Available from the
U. S. DEPARTMENT OF COMMERCE
National Technical Information Service
Springfield, Va. 22151

Table of Contents

From the Editor	vii
Introduction	1
§1. Sensitivity of explosives to mechanical action	1
§2. Mechanism of the initiation of explosion by impact	4
 Chapter I. CRITICAL CONDITIONS FOR INITIATION OF EXPLOSION	
BY IMPACT	12
§1. Focus of thermal explosion	12
§2. Critical stress condition and deformation in thin layers	14
§3. Results of tensometric measurements	20
Method of measuring pressures under impact	20
Mechanics of impact without explosive	21
Mechanics of impact with explosive	25
Optical method of measuring displacements	26
Deformation work of the charge	28
Mechanical properties of solid explosives	31
Pressure at which explosion occurs as a function of	
charge thickness	36
§4. Critical deformation conditions	39
Adiabatic induction period	39
Strength condition	42
§5. Frequency of explosions	44
Frequency curves	44
Variation of explosion frequency with charge thickness	48
Conclusions	52
 Chapter II. MECHANISM OF HEATING EXPLOSIVES TO CRITICAL	
TEMPERATURES	54
§1. Nonisometric deformation of plastic bodies	54
§2. Description of the heating mechanism	59

§3. Experimental confirmation of the heating mechanism	61
Experiments with model charges	61
Behavior of explosives under static compression	63
Frequency curve anomaly	64
§4. Examination of known models of the medium and of heating mechanisms.	66
§5. Applicability of our results to general deformation conditions . .	70
Conclusions	77
Chapter III. A QUANTITATIVE APPROACH TO THE SENSITIVITY OF SOLID EXPLOSIVES TO MECHANICAL ACTION	79
§1. The growth of explosion during mechanical action	79
§2. Classification of mechanical action	81
§3. Some general cases of mechanical action on an unconfined explosive	83
Impact on a half-space	83
Impact on a thin layer	85
§4. Quantitative evaluation of the sensitivity of explosives to mechanical action (Impact on an unconfined explosive)	87
"Minimum action" principle	87
Dependence of the sensitivity of explosives to impact on its parameters of state	89
Evaluation of the sensitivity of explosives to mechanical action.	93
Applicability limits of the obtained sensitivity estimates . . .	95
Methods of determining the quantities which characterize sensitivity	96
§5. Desensitization of explosives	102
Conclusions	104
Conclusion	106
Bibliography	109

EXPLANATORY LIST OF ABBREVIATED NAMES OF USSR
INSTITUTIONS, JOURNALS, ETC., APPEARING IN THE BIBLIOGRAPHY

Abbreviation	Full name (transliterated)	Translation
AN SSSR	Akademiya Nauk SSSR	Academy of Sciences of the USSR
IKhF	Institut Khimicheskoi Fiziki	Institute of Chemical Physics
MGU	Moskovskii Gosudarstvennyi Universitet	Moscow State University
OKhN	Otdelenie Khimicheskikh Nauk (Akademii Nauk SSSR)	Department of Chemical Sciences (of the Academy of Sciences of the USSR)
PMTF	Prikladnaya Mekhanika i Tekhnicheskaya Fizika	Applied Mechanics and Technical Physics
ZhFKh	Zhurnal Fizicheskoi Khimii	Journal of Physical Chemistry

This book presents an introduction to the quantitative theory of the sensitivity of solid explosives to mechanical action. Results of investigations into the mechanism of the initiation of solid explosives by impact are described. For the most part the results were derived by the authors.

The book is intended for workers in the physics of explosions and in the theory of explosives, for those dealing with the preparation and application of explosives, and for postgraduate students in allied fields.

FROM THE EDITOR

Many problems related to the initiation and growth of explosion by mechanical action remain unsolved, despite the many papers written on the subject. Unsolved also are problems of sensitivity and desensitization in the theory of explosives.

The initiation and growth of explosion by impact were considered by Bowden and Yoffe /11, 19/, the main attention being paid to liquid explosives. The treatment of sensitivity problems in various publications on the physics of explosions and the theory of explosives, though containing much useful qualitative information, does not conform to current concepts.

The present book fills a gap in the relevant literature, and differs from previous works by its quantitative character. It generalizes information on the problem of sensitivity, and the initiation mechanism of explosion by mechanical action, for solid explosives. The book in the main contains original results of the authors. Their investigations aided considerably in the advancement of the thermal theory of the initiation of explosives by mechanical action, developed by Khariton, Belyaev, Sukhikh, Kholevo, Bowden, and Bolkhovitinov.

The authors showed that the conditions for the deformation of explosives in the form of thin layers are the most general for the initiation of secondary explosives. Initiation of solid explosives by mechanical action is inseparably related to nonuniform heating. A new mechanism is proposed for producing localized hot spots by shear. This mechanism may be very important in the mechanics of nonisothermal deformations in general, and helped to substantiate the assumption that deformation of the charge as a whole is a necessary factor in initiating explosion by mechanical action.

The general problem of the initiation of solid explosives by mechanical action is formulated, and different experimental results are examined under various deformation conditions.

The third chapter of the book introduces a quantitative theory of solid explosive sensitivity to mechanical action. The growth of explosion from an initial disturbance is studied, and a classification of mechanical action is proposed. A number of models are investigated, leading, under certain assumptions, to a quantitative evaluation of the sensitivity of an unconfined explosive. The dependence of sensitivity on the parameters of state of the explosive is considered, and possible methods of desensitization are indicated.

The ideas developed in the monograph constitute the first systematic approach to the sensitivity of explosives. Although only solid explosives are considered, the approach may prove to be applicable to the theory of the sensitivity of other explosives (e.g., liquid explosives, ballistite, mixed solid rocket propellants, pyrotechnical mixtures).

K. I. Shchelkin

INTRODUCTION

§1. Sensitivity of explosives to mechanical action

Explosives must be handled with care because, for example, an impact on an explosive charge may bring about explosion. The ability of an explosive to explode by mechanical action is termed sensitivity of the explosive to mechanical action.

The definition of sensitivity of explosives to mechanical action omits any reference to relevant differences in explosives. These differences affect their production, handling and application, since some explosives are easily activated mechanically and require special treatment in production and handling, whereas others require minimum precautions. The first approach to the problem of the sensitivity of explosives (by Kast and Lenz) assumed that each explosive has an inherent specific sensitivity to mechanical action.

In general, the specific sensitivity of a given explosive, represented quantitatively, should serve as a measure of the danger of the explosive with respect to mechanical action on one hand, and as a measure of reliable mechanical explosion on the other hand. A knowledge of the sensitivity of various explosives could lead to a classification of the sensitivity of explosives. Two problems arising in this connection are: how to quantitatively evaluate the sensitivity, and how to check such an evaluation.

As regards the latter problem, sensitivity data on commonly used explosives have been accumulated over many decades. Clearly, initiating explosives (detonators) are more sensitive than secondary ones, and there is some certainty about the order of some explosives in such a classification. Thus, sensitivity increases in the following order: TNT (trinitrotoluene), Tetryl, RDX (cyclonite), PETN (pentaerythritol tetranitrate), tetrazene, TNRS,* lead azide, mercury fulminate. This order should serve as a reference order for checking the applicability of a given method of evaluating sensitivity. Although the reference order includes a very narrow circle of explosives, agreement with the reference order is necessary, but is still imprecise for evaluating sensitivity. In other words, disagreement with the reference order indicates incorrectness or incompleteness of the evaluation, but agreement between the orders is a proof analogous to the method of incomplete induction.

When the means of verification are limited, a theoretical substantiation of the evaluation is imperative. However, the problems associated with the quantitative evaluation of sensitivity have so far not been overcome. First, it is not clear in terms of which physical quantity the sensitivity of explosives can be expressed. Second, the specific sensitivity, postulated

* [Russian brand name of explosive.]

as a property of the explosive, should be expressed in terms of other properties of the explosive and should depend on some parameters of state, e.g., temperature. A relationship between the explosive parameters and the sensitivity determined by them could serve as a basis for developing a theory of desensitization, for understanding the relationship between sensitivity and chemical structure, etc. It is clear that the sensitivity increases as the stability of the chemical bond decreases. However, the stability of the chemical bond is in all probability not the only factor determining sensitivity, since the explosive activation energy order does not coincide with the reference order. An attempt to link the sensitivity of an explosive with its heat of formation or decomposition was also unsuccessful [1]. The mechanical properties of the explosive may also be assumed to play some role, since mechanical action is being considered. At present, what determines the variation in sensitivity of explosive compounds and the form of the relevant relationship remain unclear.

If the quantitative criterion of sensitivity in terms of the explosive properties is known, the determination of sensitivity reduces to a very simple (from the viewpoint of an experimental setup) method of measuring the physical quantity which characterizes the sensitivity, or it can be calculated from data on the properties of the explosive and parameters of state.

Possibly due to the above problems many attempts were made to find an experimental method of comparing explosives by their sensitivity. Such a laboratory method would determine the position of any explosive in the sensitivity order (and thereby the reference order could be extended) and allow one to study the influence of various factors on sensitivity, leading to a relationship between the sensitivity, and the explosive properties and parameters of state determining it. Such results would enable sensitivity to be measured quantitatively.

To compare explosives with respect to sensitivity, various (usually impact, "fall-hammer") machines were constructed. The many fall-hammer tests differ mainly by the impact conditions (geometry and dimensions of the interacting elements, method of load application, etc.). Some test devices are shown in Figure 1. It was found that different methods yield different sensitivity orders. Moreover, despite the many proposed methods, none of the resulting orders coincides with the reference order, in other words, none of the proposed methods enables a comparison of explosives with respect to sensitivity. The aim was to develop a method which, for a fixed geometry and dimensions, would be common for comparing the sensitivity of various explosives. The outcome is that either such a method could not be found, or it does not exist. The latter possibility may be correct. Indeed, the concept of higher or lower sensitivity of explosives (as presented in the reference order) was the outcome of much practical experience, in which a specific explosive was subjected to the most diverse mechanical actions. It may be that any method of comparing explosives by sensitivity should include many different tests.

With no quantitative criterion of sensitivity and with such complicated behavior of explosives under different conditions, the substantiation of any method is a difficult, if not hopeless problem, whether it involves a single-test or many-test (complex) machine. The associated problems (minimum number of machines, instruments to include in the machines, interpretation of the results if tests on different machines yield different results, etc.) remain unanswered.

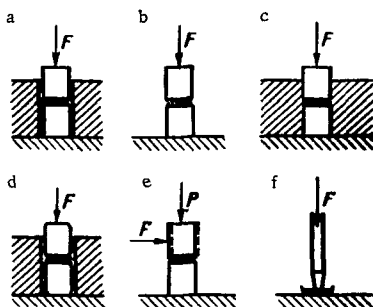


FIGURE 1. Some setups for sensitivity tests of explosives:

a — No. 1 (Kast); b — No. 2 (Kholevo);
c — No. 3 (Kholevo); d — GOST (secondary
explosives); e — Bowden — Kozlov;
f — Weller (initiating explosives).

We consider those aspects of the sensitivity of explosives to mechanical action arising in connection with the results of experiments conducted with various devices.

In view of the strong dependence of the obtained results on the type of testing device, the concept of selective sensitivity of explosives to various types of mechanical action has become widespread. Tests in devices of types a, b and d (see Figure 1) are tests for sensitivity to impact (in such devices many secondary explosives appear more sensitive than such detonators as lead azide and mercury fulminate), tests in devices of type e are tests for sensitivity to friction (initiating explosives appear more sensitive than secondary ones, but the order of initiating explosives does not

coincide with the reference order), and tests in devices of type f are tests for sensitivity to needle (stab) action (at small impact energies detonators explode; there is no coincidence with the reference order; secondary explosives undergo decomposition under the firing pin of a hammer at large impact energies).

A stab action may be regarded as one of the impact tests with a small striker area. The friction test is sometimes termed rapid shear test, indicating that the terminology (impact, friction, stab action) is of very old origin and is to some degree arbitrary. The attempt to divide the sensitivity of explosives to mechanical action into various types of sensitivity is thus equally arbitrary and questionable. For example, the attempt to distinguish the sensitivity of explosives to impact results in the same difficulties as earlier: dependence of the test results on the impact conditions; problems of evaluating the sensitivity of explosives to impact; problems of the testing method. Differentiation between sensitivities of explosives to mechanical action would be worthwhile if it yielded a difference in the initiation mechanism of explosion, i. e., some distinction similar to that which distinguishes between sensitivities of explosives to mechanical action, to thermal effects, and to a shock wave. In Kholevo's works /2, 3/, on which the current views are largely based, the difference in the test results in different devices is interpreted as a manifestation of the same mechanism under different deformation conditions, and the assumption of "selective" sensitivity of explosives "to impact" and "to friction" is criticized.

Investigations /2—8/ dealing with the effect of the mechanical action on the test results yielded very important results. Andreev and Terebilina /6/ concluded that any evaluation of the sensitivity of explosives, irrespective of the activation conditions, is devoid of practical meaning. Thus, a rigorous evaluation of potential dangers associated with any operation or of the initiation reliability can only be undertaken satisfactorily by conducting full-scale tests or somehow simulating actual conditions. Without

discussing the problem of full-scale tests, we note only that the stab-action test was conceived with the aim of imitating the impact of a firing pin on a capsule. The simulation problem cannot be solved without a quantitative description of the mechanism of the initiation of explosion.

With regard to the specific sensitivity of explosives to mechanical action, Kistiakovski and Connor concluded that such a characteristic cannot be found. Indeed, by varying the conditions of the test, they found that even the order of the mechanical sensitivities of explosives can be changed. Andreev /5/ pointed out that his conclusion is essentially similar to that arrived at by Kholevo.

The strong dependence of the test results on the activation conditions is really the crux of the problem. On the one hand, the accumulated data display the difference in explosives with respect to sensitivity and give rise to the concept of specific sensitivity as a property of an explosive. Since it is unclear which physical quantity characterizes sensitivity, this concept is to some extent only intuitive. On the other hand, the results of numerous experiments set up under the most diverse conditions of mechanical action are not only in disagreement with the reference order, but do not display a sensitivity order at all (the order varies under different conditions). It follows that one cannot speak of the sensitivity of an explosive independently of the activation conditions, or, in other words, a property such as the specific mechanical sensitivity of an explosive does not exist.

This situation affects the fundamental aspect of the problem and constitutes its main feature at present. In order to advance the investigation with the aim of either evaluating the specific sensitivity and determining the causes of different sensitivities of explosives, or evaluating the sensitivity under given conditions, it is clearly necessary to study the mechanism of the initiation and growth of mechanical explosion. Analysis of the problem of the mechanical sensitivity of explosives is to a certain extent formal, since it is based on the concept of a reference order and does not touch upon data regarding the mechanism of the process.

§2. Mechanism of the initiation of explosion by impact

The importance of studies on the mechanism of the initiation of explosion by mechanical action was first recognized when developing methods of testing the sensitivity of explosives. The different methods, and the fact that most of them involve an impact, were mentioned in the previous section. Here, the energy of the falling load (impact energy) which initiates the explosive charge is determined.

Experimental evidence supports the following facts:

1. Different explosions are not initiated by the same impact energy, but a probability of initiation corresponds to each case. The dependence of this probability (the frequency of explosions) on the impact energy (Kast and Weller fall-hammer tests), on the compression (Bowden—Kozlov fall-hammer tests) and on other facts was determined.
2. In most cases, the impact energy which causes explosion is insufficient to heat the whole charge to the ignition temperature.

3. There is no connection between the position of an explosive with respect to sensitivity to fall-hammer impact and the reference ignition temperatures.

4. The position of an explosive in the sensitivity order varies for different instruments.

Two theories of the initiation of explosion by impact have been presented: the thermal and nonthermal theories. The latter theory (which does not fit in with the second and third of the above points) postulates that chemical transformation upon impact begins as a result of molecular deformation (Kast, Eggert, Taylor and Weale, Ubbelohde and others). There are two versions of this approach: the hypothesis of critical stresses (that initiation occurs when the critical stresses of hydrostatic pressure are reached, driving the molecules of the explosive into an unstable state) and the tribochemical hypothesis (that the cause of explosion is the direct disruption of the chemical bond in the explosive molecules due to shear stresses).

A study of the effect of high pressures on the thermal decomposition of a number of explosives showed that as high a pressure as 45 kbar in general has little influence on the rate of decomposition /9—11/. In addition, Bridgman /12/ has examined the effect of hydrostatic pressures up to 100 kbar on a number of explosives; explosion was not initiated, whereas these explosives can be exploded by impact, where the pressure is considerably lower. In connection with the tribochemical hypothesis it should be noted that, upon deformation, for example of organic explosives (molecular crystals), it is impossible to immediately destroy the molecules, since the energy of the intramolecular bonds is much higher than that of the intermolecular ones. These conclusions demonstrate the physical inconsistency of the nonthermal hypotheses.

According to the thermal theory, a mechanical action (for example, an impact on an explosive charge) heats it up, resulting in a rapid chemical reaction. This theory was proposed by Berthelot, and developed by Khariton, Belyaev, Bowden, Kholevo, Sukhikh and Bolkhovitinov.

How does the thermal theory explain the facts? Since the energy of the impact causing explosion is usually insufficient to heat the charge even to the reference ignition temperatures, it is clear that adiabatic compression of the explosive proper does not initiate explosion (the small rise in temperature, due to adiabatic compression up to a value characteristic of impact, is confirmed by rough estimates /13/). This led to the hypothesis of localized hot spots in a charge upon impact /13/. The possibility in principle of a localized initiation was demonstrated in experiments of Belyaev /14/ with wires measuring the order of a micron, through which a current was discharged.

According to Garner /15/ and Muraour /16/, in order to cause a self-propagating explosive change, the "simultaneous" (in the course of 10^{-13} sec) decomposition of two or three neighboring molecules (e. g., for lead azide: two neighboring N_6 groups) is sufficient. Bowden and Singh /11/ irradiated various explosives (including lead azide) with high-speed particles, and showed that the initiation of a self-propagating process requires high-intensity radiation (a macroscopic character). (Bowden criticized the tribochemical hypothesis as not satisfying the requirement of a macroscopic process /18/.)

Consider the causes of the localized character of the hot spot. First consider liquid explosives. It is known that the explosion of a charge is easily initiated if gaseous inclusions are present in the explosive. This phenomenon was investigated extensively by Bowden et al. /19/. It is believed that in this case the hot spot caused by adiabatic compression of the gaseous inclusions is responsible for explosion. However, a simple comparison of the thermal relaxation time of a gaseous bubble with the characteristic time of the impact shows that the compression of gaseous inclusions less than 0.1 mm in diameter should, in practice, be isothermal /20/. In the absence of gaseous inclusions the detonation of liquid explosives is far more difficult, as fairly large impact energies are required. It is usually believed that in this case explosion is initiated by viscous heating. Bolkhovitinov /20/ proposed a mechanism for heating, according to which initiation may result due to heat release upon the crystallization of supercooled liquid under high pressure. If, however, we use the heats of fusion (crystallization) presented in the literature, the corresponding temperature required is approximately 60°C, and the heat of fusion under pressure can hardly be expected to increase by an order. In many cases the cavitation mechanism of initiation may be very important for explaining explosion of liquid explosives: the burst of cavities due to tension results in explosion /21/. The important role played by microjets of liquid, which may appear upon the burst of cavities, and by rapid compression of the gaseous inclusions, during initiation, is noted in /22/.

Consider now solid explosives (in the following, unless specifically indicated, only solid explosives will be treated) and the causes of localized hot spots in them. If the charge contains gaseous inclusions, their adiabatic compression may produce a high temperature. Khariton /3/ also mentions the nonuniformity of inelastic deformation as another cause, drawing special attention to the nonuniformity of deformation owing to the nonuniformity of the initial system (interparticle friction, plastic deformation of individual particles, their destruction). Kistiakovski and Connor /7/ concluded likewise. In addition, a cause of localized hot spots may be the nonuniformity of inelastic deformation of the charge as a whole.

Of these three possible causes of localized hot spots, the true cause can be decided by the experiments of Kholevo /2, 3/ in instruments Nos. 1, 2 and 3 (see Figure 1). In instrument No. 2 the explosive charge can be deformed in an unconfined volume, and therefore it is also termed the instrument with free material flow. In instrument No. 1, the explosive can be extruded into a gap between rollers and a sleeve. In instrument No. 3, extrusion into a gap is eliminated by a ring of soft metal, thus constituting instrument No. 1 with zero gap. The experiments, conducted mainly with regular explosives in the bulk dispersed state, yielded the following results:

- a) The tested explosives do not explode in instruments Nos. 1 and 3 if the gap is sufficiently small, even under high impact energies;
- b) The explosives explode in instruments Nos. 1 and 2 if the gap is not too small; for the same impact energy, some explosives under free-flow conditions (instrument No. 2) yield a higher frequency of explosions than under conditions of hindered flow (instrument No. 1), whereas other explosives react conversely.

Some important conclusions follow from these simple and easily reproducible experiments:

1) Compressed gaseous inclusions subjected to impact do not result in the initiation of explosion.

2) Nonuniform inelastic processes associated with deformation and destruction of individual grains, as well as their friction with one another, do not result in the initiation of explosion.

3) Inelastic deformation (flow according to Kholevo) of an explosive charge as a whole is a necessary factor for the initiation of explosion.

4) The high stresses created in a charge upon impact (in the absence of flow) do not result in the initiation of explosion.

5) The conditions of deformation have a significant influence on the initiation of explosion.

The latter three conclusions are discussed in detail in Kholevo's works and are used, in particular, to criticize the hypothesis of critical stresses, when discussing the variations in the order of sensitivity due to different experimental conditions. According to Kholevo, localized hot spots form upon rapid inelastic deformation, depending on the deformation conditions, the physicochemical properties of the explosive and the rate of straining.

As regards the probability character of the tests, until now no corresponding mechanism of initiation has been proposed, probably due to the irregular experimental conditions upon which the test results depend. Regulation of the experimental conditions narrows down the frequency curve.

In addition Khariton /13/ has noted the quasistatic character of the process under impact, distinguishing, in particular, between the mechanical sensitivity and the sensitivity to a shock wave.

Thus, this qualitative general analysis of the mechanical initiation of explosion along different paths points to the fact that this phenomenon should be examined with the aid of methods of the mechanics of inelastic continuous media and the theory of heat conduction, i.e., the simultaneous application of the equations of deformation and the equation of heat conduction with (mechanical and chemical) heat sources.

In view of the associated difficulties (even for the simplest model of a medium and the simplest deformation conditions), the problem is usually divided into two stages, since the rate of the chemical reaction depends exponentially on the temperature and is important only at high temperatures. The first stage involves heating the explosive to a critical temperature in the presence of deformation due to the dissipation of energy of the external action. The second stage involves thermal self-ignition in the hot-spot zone. The critical temperature serves to distinguish between the first, purely mechanical stage, and the second, explosion stage, which is associated only with the acceleration of the chemical reaction.

The critical temperature for various explosives and its dependence on different factors is found using the techniques of the theory of thermal explosions (these problems will be analyzed in Chapter I, §§ 1 and 4). According to Rideal and Robertson /23/ and Bowden /19/, the critical temperatures and the sizes of the localized hot spots for the most common explosives are respectively 400–600°C and 10^{-3} – 10^{-5} cm.

Consider the first stage. Theoretical analysis of mechanical heating under definite deformation conditions reduces to the solution of unsteady,

nonisothermal equations of deformation. The theory of nonisothermal deformations is currently at the initial stage of development and is still unsuitable for application [24—26]. The experimental approach must therefore be used.

Sukhikh and Khariton [27] experimented with large charges of cast TNT under impact, and observed that the explosive melts at the slip planes on which the maximum shearing stresses act, leading to intense plastic deformation and decomposition. They concluded that melting is a powerful regulator of the heating process, limiting the temperature rise. Earlier when studying friction of metals, Bowden et al. [28] showed that the maximum temperature under friction is limited by the metal of the rubbing surfaces with the lower melting point. The appearance of hot spots at the slip planes in the experiments of Sukhikh and Khariton shows once more that, despite the small critical sizes of the hot spots, deformation of the charge as a whole is decisive in the initiation of explosion. The assumptions regarding melting and the hot spot were also adopted by Bowden [19] and confirmed experimentally. The lowest melting points of admixtures with high sensitization were interpreted as the critical temperatures of the hot spot, lying within the interval 400—600°C. These experiments give an idea of the sensitization mechanism of admixtures with high melting points. According to Bowden, initiation in this case is due to heating of inert particles by friction with one another or at the solid surface of the colliding bodies.

If the melting point of the explosive is close to (or higher than) the critical temperature, then, according to Bowden, effective hot spots may arise due to friction of particles of the explosive. This was illustrated by a series of detonators which deflagrate by heating before the onset of melting. By testing explosives in a device of type e (see Figure 1), Bowden showed that explosion can be initiated under fairly low rubbing pressures, whereas he did not succeed in exploding secondary explosives under these conditions.

The melting point for most secondary explosives is much lower than their standard ignition temperature. This introduced difficulties when explaining their heating up to the critical temperatures, and drew attention to other mechanisms unrelated to the assumption of melting as the heating-up limit or disproving this assumption. Bowden [19], who was unfamiliar with the works of Kholevo, concluded that the initiation of secondary explosives by impact is due to adiabatic compression of gaseous inclusions. To support his point of view, he noted that secondary explosives do not explode by rapid shear (Figure 1, e) (unlike the effect of impact) even under considerable rubbing pressures, i. e., when the gaseous inclusions, if preserved, are already compressed.

Kholevo proposed the following explanation of heating under impact: at the first stage of the impact, owing to deformation of individual particles and their friction with one another, the grain boundaries of the explosive melt, and a two-phase system forms, whose deformation results in the liquid layers being heated to high temperatures. The system thus formed resembles a viscoplastic body. To characterize its mechanical properties use was made of the concept of fluidity, but in a number of cases, for simplicity, the qualitative results were illustrated by the model of viscous

fluid. In this approach one of the parameters determining the hot-spot temperature is the rate of straining; the role of the pressure reduces to providing sufficient rates of straining under given activation conditions and given system fluidity.

The assumption that melting defines the extent of heating is contradicted by Kozlov from the fact that the melting point increases considerably with increasing pressure. For sufficiently high pressures, effective hot spots can therefore be obtained during inelastic deformation in the solid phase. Kozlov /36/ conducted experiments according to the scheme of type e (see Figure 1); he increased the rubbing pressure very much as compared with the experiments of Bowden, and obtained explosions in every tested explosive. Kozlov attributes the inelastic deformation process responsible for the hot spots to external (dry) friction between the explosive charge and the solid surfaces of the containing walls, assuming that friction between the explosive particles in the compressed charge is ineffective. For this process the rate of shear is very important, since it affects the rate of heat release in the plane of friction relative to the rate of heat transfer.

The many approaches to the problem have contributed not only to a many-sided discussion of the possible influence of specific factors on the heating-up process, but have also yielded much varied experimental material. The assumption of melting was for a long time omitted in treatments of the problem, until Bolkhovitinov /29—31/ finally considered the role of pressure. This generalization yielded the result that the melting temperature defines the heating-up limit, but this limit depends on the pressure. Thus, effective heating upon inelastic deformation is possible only in a volume subjected to uniform compression; the value of the required pressure is then determined by the fact that the melting temperature should be at least equal to the critical temperature of the hot spot.

The necessity in Kozlov's experiments of applying a high pressure to initiate explosion, while disproving the assumption of the normal melting temperature as the limit of heating, can itself now be explained by a generalized assumption of melting. Bolkhovitinov /31/ assumed that the Clausius—Clapeyron equation defines the dependence of the melting temperature on pressure, and was the first to attempt a mathematical formulation of the critical conditions for the formation of an effective localized hot spot. For this he used a model of a perfectly plastic body and made simplifying assumptions with regard to the character of heat transfer, to the constancy of the plastic deformation strength, and to the critical conditions of self-ignition at the hot spot. The influence of the rate of action on the initiation of explosion is significant, and is taken into account by the condition of critical plastic deformation strength.

Bolkhovitinov used the following linear relationship between the melting temperature T_{mel} and the pressure:

$$T_{\text{mel}}(P) = T_{\text{mel}}^{\dagger} + \alpha P, \quad (1)$$

where $\alpha = 0.02 \text{ deg/atm}$ (this value of α was obtained by averaging the results of Bridgman /32/, who studied the variation in melting temperature with pressure for many organic substances).

According to the generalized assumption of melting as the limit of the mechanical heating of solid explosives, and following (1), the pressure necessary to initiate explosion should be proportional to the difference between the critical and melting temperatures under normal conditions. Bolkhovitinov /30/ assumed, for simplicity, that the critical temperature is similar to the ignition temperature T_{ign} for a 5-sec inhibition; by comparing the difference ($T_{\text{ign}} - T_{\text{mel}}$) with the pressures developing upon impact, he obtained (with the aid of Leitman's results /33/) the expected correspondence. Without being critical of Bolkhovitinov's work /30/, we note that even such a quantity as the pressure necessary to initiate explosion (according to the generalized assumption of melting) may be correlated approximately with the difference between the ignition and melting temperatures, but in no way with the ignition temperature itself. (Attempts to directly correlate the sensitivity of explosives to impact with their thermal sensitivity, for example with the ignition temperature, are still encountered /34, 35/.)

Thus, the thermal theory of mechanical initiation of explosives may explain the facts and, despite the different viewpoints on individual problems, this theory is commonly accepted in the current literature (except possibly for hypersensitive explosives, like nitrogen iodide, the nature of whose sensitivity remains unclear /1, 19, 36/).

Nevertheless, many basic assumptions on which the explanation of mechanical initiation is presently based follow from experimental results, and are without, or have insufficient, physical foundation. This even refers to such an assumption as localized initiation of explosion. In particular, the importance of this localization is unclear, as well as whether nonlocalized (uniform) mechanical heating is at all possible in general. The reason for the inoperation of the mechanism of compression of gaseous inclusions for solid explosives is unknown. As regards the heating mechanism of explosives under inelastic deformation, despite the many publications dealing with the initiation of explosion under various deformation conditions, the mechanical conditions of deformation under particular conditions has remained unstudied, and most of the experimental material consists of explosion frequency and its dependence on specific factors. Differences in the literature on the heating mechanism, the model of the medium corresponding to solid explosives, and the deformation conditions are based mainly on the effect of the process (explosion frequency) and are hypothetical in character. There is no standard approach to these problems. The models of solid explosives presented in various works include a Newtonian fluid /2, 37, 38/, viscoplastic body /2/, perfectly plastic body /31, 39/, and bodies comprising elastic and viscous elements.

The absence of concrete data on the deformation process hinders even a comparative discussion of the proposed heating mechanisms, and therefore only the well known ones are mentioned in the introduction, without a critical analysis.

The present work treats the mechanism of mechanical initiation of solid explosives mainly by the example of impact, and an attempt is made at a quantitative approach to sensitivity problems for solid explosives. The assumption of melting as the heating-up limit, with allowance for the role of pressure, opens possibilities for a quantitative description of the process.

In the first chapter, the results of experimental measurements are applied to determine the critical conditions for the initiation of explosion (critical deformation conditions) in instrument No. 2.

The second chapter presents a discussion of the character of the deformation of model plastic bodies, as a result of which a new heating mechanism for solid explosives is postulated. This mechanism is in good agreement with the experimental results. The proposed mechanism is used to formulate the problem of the initiation of solid explosives by mechanical action.

In the third chapter, problems presented in §1 of the Introduction are studied and the possibility of a quantitative approach to solid explosives is examined. In this connection a classification of mechanical actions is proposed. In addition, quantitative estimates of sensitivity are derived, under various assumptions, for one class of mechanical actions.

In conclusion, the directions in which future research on the mechanical sensitivity of explosives might be undertaken are discussed in brief.

Chapter I

CRITICAL CONDITIONS FOR INITIATION OF EXPLOSION BY IMPACT

§1. Focus of thermal explosion

To estimate the critical temperatures one has to study thermal explosion by mechanical action.

The solution of the problem of thermal ignition consists in determining under which conditions the rate of heat production by chemical reaction is greater than the rate of heat loss to the surroundings, and in establishing the temporal characteristics of the process /40—43/.

A classical problem in the theory of thermal explosion is that of the rate of chemical reaction of an explosive mixture placed in a vessel of definite form and size with an assigned temperature at the walls. However, in our case the explosive charge (the principal mass of explosive) contains a localized hot spot of unknown temperature distribution.

The process of self-ignition of a hot spot is usually described with the aid of the following scheme /23, 31, 44—50/. Suppose at some instant an infinite mass of explosive contains a spherical focus of radius r and temperature T_1 . We require the critical relationship between r , T_1 , the temperature T_0 of the principal mass of the explosive surrounding the focus, and the thermochemical and kinetic constants corresponding to thermal self-ignition. This problem was correctly solved in /48/, the solution having the form

$$\frac{r^2 Q E z}{\lambda R T_{cr}^2} e^{-\frac{E}{RT_{cr}}} \cong 12.1 \left[\ln \frac{E}{RT_{cr}^2} (T_{cr} - T_0) \right]^{0.6} \quad (2)$$

where Q is the heat produced by the reaction per unit volume; E is the energy activation; z is a preexponential factor; λ is the thermal conductivity of the explosive; R is the gas constant.

For $T_1 > T_{cr}$ explosion occurs after some induction period, and for $T_1 < T_{cr}$ the temperature falls rapidly at the focus. It is significant that the induction period for self-ignition of the focus is close to the adiabatic induction period, which is given by

$$\tau_{ad} = \frac{c p R T_1^2}{Q E z} e^{\frac{E}{R T_1}},$$

where c and ρ are the specific heat and density of the explosive (in the following assumed to equal 0.3 cal/g · deg and 1.6—1.8 g/cm³, respectively).

Hence the critical temperatures can be directly estimated. In the case of impact the induction period should not exceed at least the impact time τ_{im} whose order of magnitude (for example, for pile-driver tests) is 10^{-3} sec. In other words

$$\frac{cpRT_{\text{cr}}^2}{QEz} e^{\frac{E}{RT_{\text{cr}}}} \leq \tau_{\text{im}} \approx 10^{-3} \text{ (sec)}. \quad (3)$$

The above expressions hold to the extent that the decomposition of the explosives may be represented by zero-order reactions. In general most explosives decompose autocatalytically [51] according to the equation

$$\frac{d\eta}{dt} = (1 - \eta) z e^{-\frac{E}{RT}} + \eta (1 - \eta) z_1 e^{-\frac{E_1}{RT}},$$

where η is the decomposition rate.

The first term of the equation describes the monomolecular component of the reaction rate, and the second term describes the autocatalytic component, whose activation energy and preexponential factor are respectively E_1 and z_1 . For some decomposition rate η_0 the monomolecular and autocatalytic components of the reaction rate are equal, η_0 being determined by

$$\eta_0 = \frac{z}{z_1} e^{\frac{E_1 - E}{RT}}.$$

For most explosives this latter expression has the order of magnitude $10^{-1} - 10^{-2}$ (because the values of E and E_1 are close to each other and η_0 is weakly dependent on the temperature). Consequently, for $\eta < \eta_0$ one may neglect autocatalysis and burning, and assume that the decomposition proceeds according to a zero-order reaction.

Consider now the adiabatic induction period. Most of the adiabatic self-ignition period is occupied by self-heating, by an amount $\frac{RT^*}{E} / 48$, which for the temperatures of interest gives for the decomposition rate

$$\eta_1 = \frac{cpRT_{\text{cr}}^2}{QE} \approx 10^{-3},$$

i.e., $\eta_1 < \eta_0$. Thus, the zero-order reaction reflects well the process under consideration.

It will now be shown that the order of magnitude of the induction period in the case of initiation by impact is not more than 10^{-5} sec, and therefore condition (3) can be rewritten as

$$\frac{cpRT_{\text{cr}}^2}{QEz} e^{\frac{E}{RT_{\text{cr}}}} \leq 10^{-5} \text{ (sec)}. \quad (4)$$

If we use formula (4) with the equality sign to estimate the critical temperatures in the case of impact, then a calculation based on known

kinetic data /52—54/ yields for common explosives (TNT, Tetryl, RDX, PETN and others) critical temperatures T_{cr} in the interval 400—600°C. In this case the right-hand side of (2) remains approximately constant and equal to 25, i.e.,

$$\frac{r^2 Q E z}{\lambda R T_{cr}^2} e^{-\frac{E}{R T_{cr}}} \approx 25. \quad (5)$$

Comparing expressions (4) and (5), the order of magnitude of the critical radius of a hot spot is found to be not larger than 10^{-4} cm (for organic explosives λ is on the average $2.4 \cdot 10^{-4}$ cal/cm·sec·deg).

§2. Critical stress condition and deformation in thin layers

We now discuss the conditions for the formation of an effective hot spot under inelastic deformation. First consider the nature of the deformation and the medium. Fairly large solid explosive charges both in a cast and a dispersed state constitute an aggregation of many small particles, within each of which there is anisotropy. However, owing to the diverse random orientation of the various particles, we assume (as is usually done for polycrystalline bodies) that the material is isotropic and homogeneous. In this case the appearance of effective hot spots is associated with inelastic deformation of the explosive charge as a whole, and not with the displacement of individual particles and their friction with each other. We assume, in addition, that melting is the limit of heating upon deformation of solid explosives.

The direct theoretical analysis of mechanical heating consists in solving the unsteady nonisothermal equations of deformation, which allow for the variation of the mechanical properties of the medium with temperature. Since even under the simplest conditions this problem at present cannot be solved for any medium, and there are no suitable methods for experimental measurement of the temperatures of transient localized hot spots in a solid deforming opaque medium, fairly simple indirect techniques have yet to be found.

One could, for example, introduce various simplifications and obtain in each case some picture of the mechanical behavior and initiation of the explosive without actually studying the real process. This picture could then be compared with experimental data. Such a comparison should show the validity of any specific assumptions.

One problem of interest would be to consider adiabatic deformation. However, we encounter here tremendous difficulties. Thus, in particular, the mathematics of the mechanics of deformable media is developed mainly for analysis of small deformations (relative deformations small compared with unity) /26/, which are clearly insufficient for producing high-temperature hot spots. If this difficulty could nevertheless be overcome, even then the situation would remain very complicated, since in the adiabatic case, as deformation and heating develops, the medium becomes locally

plastic and inhomogeneous (the mechanical properties depend on the temperature); however, the theory of plastic inhomogeneous media considers simpler forms of inhomogeneity /55/.

Another interesting case occurs if one assumes that hot spots upon deformation do not modify the mechanical properties of the medium. Then the distribution of the stresses and displacements of the medium upon deformation should be the same as in the isothermal case. Thus, one could use the known (isothermal) solution for a formal calculation of the hot-spot temperature and obtain some picture of the behavior of the explosive. It is clear that the initial stage of deformation for low-temperature hot spots should be well described by the isothermal solution, and so nonisothermal effects could be regarded as a departure from the isothermal solution; the main role in this respect belongs to experiment. This case is also complicated, since the difficulty of investigating finite (large) deformations remains and, in addition, it becomes necessary to consider the equations of heat conduction with a complicated source distribution. However, retaining this approach, the problem could be simplified even further by obtaining some conditions necessary for the initiation of explosion by a generalized assumption of melting and the mechanical characteristics of the explosive, known from ordinary compression experiments (static and isothermal) of cast and pressed explosive samples.

With regard to the generalized assumption about melting, the pressure of uniform compression necessary to initiate explosion is determined by the fact that the melting temperature should be at least equal to the critical temperature of the hot spot. The critical stress P_{cr} is the required hydrostatic pressure, and the necessary condition for initiation is

$$P \geq P_{cr}, \quad (6)$$

i.e., a condition for critical stresses. From a physical point of view this condition has nothing in common with the nonthermal hypothesis of critical stresses, discussed in the Introduction. According to this hypothesis, the attainment of the critical stress is a necessary and sufficient condition for the initiation of explosion. In the present case, condition (6) is only a necessary condition for the hot spot to attain the critical temperature, while the hot spot itself should be created by inelastic deformation. Therefore Kholevo's criticism of the critical stress hypothesis, which was based on experiments in instrument No. 3, namely, in the absence of flow, has no relation to the critical-stress conditions (6).

The critical stress can be found by the Clausius — Clapeyron equation, if the critical temperature is known. Using expression (4) with the equality sign, we obtain

$$\begin{aligned} T_{mel}(P_{cr}) &= T_{cr}, \\ L &= T_{mel} \frac{dP}{dT_{mel}} \Delta v, \\ \frac{cpRT_{cr}^2}{QEz} e^{\frac{E}{RT_{cr}}} &= 10^{-5} (\text{sec}), \end{aligned} \quad (7)$$

where L is the specific heat of fusion; Δv is the difference in the specific volumes of the liquid and solid phases.

The Clausius — Clapeyron equation, however, introduces difficulties, since the heats of fusion and the difference in the specific volumes of the liquid and solid phases, and all the more so their variation with pressure, are not known for all explosives (for some explosives, according to data given in /56/, the following values of $\alpha = dT_{\text{mel}}/dP$ under normal pressure are relevant: for dina* $\alpha = 0.022$; for nitroglycerine $\alpha = 0.029$ deg/atm). For rough estimates we use the linear approximation (1) for the pressure dependence of the melting temperature with $\alpha = 0.02$ deg/atm. This yields the critical stress

$$P_{\text{cr}} = \frac{T_{\text{cr}} - T_{\text{mel}}}{\alpha};$$

$$\frac{cpRT_{\text{cr}}^2}{QEz} e^{\frac{F}{RT_{\text{cr}}}} = 10^{-5} \text{ (sec).} \quad (8)$$

For most secondary explosives the difference ($T_{\text{cr}} - T_{\text{mel}}$) is 200—500°C; hence $P_{\text{cr}} = 10^4 - 2.5 \cdot 10^4$ atm.

The requirement of high pressures for the initiation of explosion by mechanical action follows from Bowden — Kozlov impact, fall-hammer tests (Kozlov's data in Figure 2 are quoted in /36/). However, compression

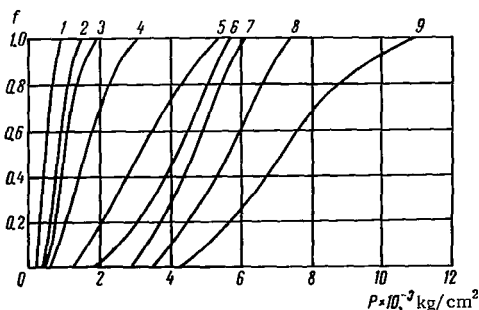


FIGURE 2. Explosion frequency vs. compression pressure (obtained on a Bowden — Kozlov impact fall hammer):

1 — mercury fulminate; 2 — tetrazene; 3 — TNRS;
4 — lead azide; 5 — PETN; 6 — RDX; 7 — Tetryl;
8 — trinitrophenol; 9 — TNT.

pressures for secondary explosives corresponding to 100% explosions on the frequency curve lie between 5000 (PETN) and 11,000 atm (TNT), which is by a factor of 2—2.5 lower than the values expected from an estimate of the critical stress P_{cr} . In the following this apparent discrepancy will be explained. It is noteworthy also that such detonators as mercury fulminate, tetrazene, TNRS and lead azide, which upon heating to ignition temperatures do not melt, require appreciable compression pressures for initiation, although smaller than for secondary explosives. In other words, from the viewpoint of the condition of critical stresses for these detonators ($T_{\text{cr}} - T_{\text{mel}} > 0$). In general, such a behavior of detonators should not

yet be regarded as a contradiction. Thus, for example, the ignition temperature for lead azide under a 5-second induction period is 345°C, and a sensitizing effect in Bowden's experiments with admixtures was obtained for melting temperatures of the latter starting at 500°C. Therefore if the melting temperature of lead azide lies between 345 and 500°C, no contradiction arises. The situation with mercury fulminate, tetrazene and TNRS is similar.

* [Russian brand name of explosive.]

We turn to another problem related to the condition of critical stresses, i. e., to the necessity of obtaining pressures of the order of 10^4 atm. It is known that in ordinary (static and isothermal) tests of mechanical properties, solid secondary explosives may suffer a fairly small plastic deformation and brittle fracture under stresses of the order of 10^2 kg/cm². The problem then is to attain under inelastic deformation pressures which exceed the strength of the medium by two orders. For this, some special conditions of deformation are clearly needed. The numerous methods (including those presented in Figure 1a, b, d, e, f) for testing the sensitivity of explosives to mechanical action (in particular to impact) all involve deformation in thin layers, for which high pressures can indeed be attained on a low-strength medium. The wide use of thin layers in sensitivity tests of explosives and in investigations of the dependence of the initiation of explosion on the action to which they are subjected is not accidental. This is some confirmation of the generalized assumption of the role of melting or, alternatively, of the critical-stress condition.

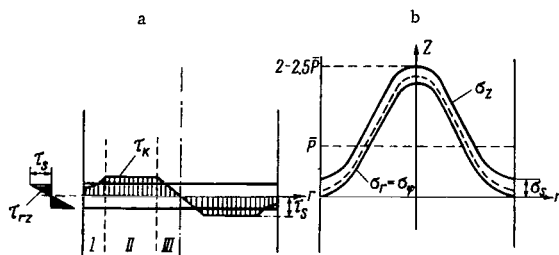


FIGURE 3. Distribution of shearing (a) and normal (b) stresses over the sample.

Deformation in thin layers, dealt with in the present work, is one of the fundamental problems of the pressure treatment of metals [57, 58]. With a view to obtaining a clear picture of the behavior of explosives by means of necessary conditions for initiation and subsequent investigation of the process, the simplest deformation conditions will be chosen from the viewpoint of experimental measurements and the best developed theory. In this respect, what is termed as "the technological procedure for placing cylindrical samples," which coincides with the tests in instrument No. 2 (in Figure 1), is widely used in sensitivity tests of explosives. Deformation under such conditions (axisymmetric problem) was thoroughly investigated for plastic metals: the stress distribution in the deformed sample was found (Figure 3), and it was shown that under plastic deformation (the model of the medium took the form of a perfectly plastic body) the mean pressure \bar{P} is related to the yield stress σ_s of the material, the height (thickness) h of the sample and the diameter D (for $h/D < 0.125$) as follows:

$$\bar{P} = \sigma_s \left(1 + \frac{D}{3\sqrt{3}h} \right). \quad (9)$$

Despite the approximate (engineering) character of the solution, both formula (9) and the stress distribution (see Figure 3) are well confirmed experimentally /57, 58/.

The sample deformation is largely determined by the conditions at the contact surfaces ($z = \pm h/2$). The contact surface is divided into three zones of different radii, depending on the character of the deformation. In zone I (the gliding zone of size close to h), where the normal stresses (σ_z) are fairly small, the shearing stresses at the contact surface (τ_k) increase with increasing normal stresses according to the Coulomb law $\tau_k = \beta \sigma_z$ (β being the Coulomb friction coefficient). In zone II (the damping zone of size approximately $2h$ less than the sample radius) the Coulomb law is inapplicable, since the normal stresses there are larger than in zone I, and the value of τ_k cannot exceed its maximum possible value, namely, the shearing yield stress of the material $\tau_s = \sigma_s/\sqrt{3}$. (The Coulomb law is inapplicable if the normal pressure exceeds twice the yield stress of either member of the friction pair. In this case the shearing stress is equal to the shear limit, the deformation (as a function of the conditions) extends into the weak material, and for plastic bodies there is no difference between friction and plastic deformation.) In this zone the shearing stress τ_k is constant and equal to τ_s . In zone III (the adhesion zone of radius close to h), the shearing stresses decrease independently of the normal stresses. For smaller h/D , zone II is comparatively larger than zones I and III. For $h/D < 0.125$, zone II is so much greater that the condition $\tau_k = \tau_s$ can be extended to the whole contact surface, thus yielding formula (9). The condition $\tau_k = \tau_s$ makes the present situation equivalent to cases of absolutely rough pistons to which the deformed medium strongly adheres (the pistons are regarded as absolutely rigid). In this case /59/ the problem can be solved by the more rigorous methods of plasticity theory (particularly the two-dimensional theory /63/, whose analogy with the axisymmetric theory is widely used). The solution is the same and is applicable not only to compression, but also to separation. This solution is used to explain the increased strength of brazing and soldering.

Formula (9) agrees fairly well with brittle separation experiments /59/, if σ_s is replaced by the ultimate strength σ_{ult} , which is equivalent to equating τ_k to the ultimate shearing strength τ_{ult} .

$$\bar{P}_{ult} = \sigma_{ult} \left(1 + \frac{D}{3\sqrt{3}h} \right). \quad (10)$$

The above data must now be applied for our purposes. Assuming that formula (10) holds for the endurance of brittle systems under compression, the curve of \bar{P} vs. h/D yields curve I (Figure 4), attaining (average) pressures higher than those for which the sample will be destroyed. Let us call relation (10) the endurance condition. If now for simplicity we assume that the critical average pressure \bar{P}_{cr} for which explosion is possible is determined mainly by the critical stress P_{cr} , and is independent of h/D , then the condition of critical stresses in instrument No. 2, namely

$$\bar{P} \geq \bar{P}_{cr}, \quad (11)$$

is represented on the graph (Figure 4) by the region lying above the straight line (II), parallel to the abscissa axis. The shaded area represents the explosion region.

Conditions (10) and (11) are given for instrument No. 2 and are expressed in terms of the average pressure, the value of which is obtained by

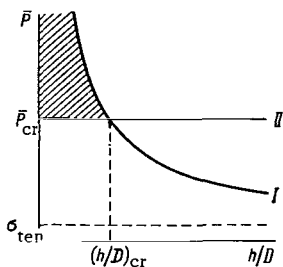


FIGURE 4. Assumed picture of the explosive behavior.

averaging the distribution of σ_z (see Figure 3) over the area of the piston. Let us clarify some points with regard to the critical-stress condition (II) in instrument No. 2, the latter condition having a more complicated interpretation than the earlier introduced critical-stress condition (6), namely $P > P_{cr}$. The quantity \bar{P}_{cr} will be termed in the following the critical stress in instrument No. 2, and P_{cr} the true critical stress. The distribution $P = \frac{1}{3} (\sigma_z + \sigma_r + \sigma_\theta)$ of the hydrostatic

pressure over the radius is of interest in connection with the condition of critical stresses $P > P_{cr}$, and is represented in Figure 3 by the dashed curve, the pressure varying from a maximum (which depends on h/D) at the center

($P_{z=0} = 2 - 2.5 \bar{P}$) to $P_{z=R} = \frac{1}{3} \sigma_{ult}$ at the sample edges.

For most secondary explosives $P_{cr} \gg \sigma_{ult}$. Therefore an effective hot spot can never form at the sample edges, because the condition $P > P_{cr}$ cannot be satisfied. On the other hand, an effective hot spot cannot form at the center either, even if the hydrostatic pressure exceeds the true critical stress, since the condition of critical stresses $P > P_{cr}$ is only a necessary condition for the formation of an effective hot spot which is created by inelastic deformation, this deformation increasing from the center toward the edges of the sample.

The location of the effective hot spot should be determined by the following. The hydrostatic pressure should not be less than the true critical stress; the hot-spot temperature under inelastic deformation should not be less than the critical (since we are dealing with a localized hot spot, the rate of straining should also be sufficiently high so that the heat cannot escape). The average pressure under which a hot spot of just the critical temperature forms, for the hydrostatic pressure at the focus equal to the true critical stress, is \bar{P}_{cr} . Thus, this quantity should depend on the properties of the explosive and the parameters of the action to which it is subjected, namely h , D and u (u being the speed of the piston) or any independent combination of them, say h , h/D and u . (The validity of this conclusion with regard to hot-spot formation under deformation follows from the fact that the formation of effective hot spots occurs as a result of inelastic deformation of the charge as a whole.) The necessary condition for initiation of explosion in instrument No. 2, i.e. $\bar{P} > \bar{P}_{cr}$, refers to a thin layer and apparently depends mainly on the quantity P_{cr} , since the mere necessity of deformation in thin layers follows from the necessity of attaining P_{cr} . It is this consideration on which the assumptions rest. The quantity \bar{P}_{cr} is assumed to be independent of h/D , this form yielding the simplest representation in $\bar{P}-h/D$ coordinates. This latter assumption

should not, however, give rise to fears, since the independence of h/D and the consideration that \bar{P}_{cr} may depend on h and u will be examined.

The following assumptions are made:

- 1) \bar{P}_{cr} is independent of h/D ;
- 2) \bar{P}_{cr} is allowed to depend on h and u ;
- 3) the concepts of the mechanical properties of the explosive, obtained under static and isothermal conditions, are carried over to the case of impact;
- 4) solution (10) of the isothermal problem is used;
- 5) this solution is assumed to hold for brittle fracture by compression.

Thus, with the aid of the derived critical-stress and endurance conditions, a clearer picture of the explosive behavior in instrument No. 2 is obtained. This picture can be improved with the aid of additional experimental results.

§3. Results of tensometric measurements

Method of measuring pressures under impact

According to the assumed behavior of the explosive (see Figure 4), one has to measure the average pressure in instrument No. 2 upon impact with samples of various ratios h/D . The pressure during impact was measured by a tensometric method [31, 61, etc.]. The apparatus is shown in Figure 5. The pressure pickup consisted of the lower roller of a stamping machine with a bifilar winding of insulated constantan PEK-0.03 wire. The ends of the winding were attached to the roller by a solution of photographic film in dichlorethane, after which the winding was coated with a layer of BF-6 glue. The pickup was then maintained at a temperature of 150°C for several hours in order to polymerize the glue. The resistance of the pickup was about 600 ohm. The pickup was calibrated under compression in a press up to 20,000 atm (the pickup resistance varies by about 1 ohm for each 5000 atm).

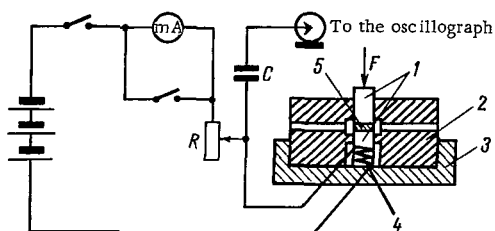


FIGURE 5. Design of apparatus and connection of the pickup to the oscillograph:

1—rollers; 2—sleeve; 3—bedplate; 4—pickup; 5—charge.

The pickup was also calibrated under impact by a fall-hammer machine, the calibration results being in agreement. The pickup was connected to an

oscillograph (OK-17, OK-24V, and OK-24M double oscillographs equipped with a photoattachment were used) by a simple electric circuit (see Figure 5). The input resistance of the oscillograph was increased to 2 Mohm so that the time constant of the measuring circuit would be far greater than the duration of the process, thus avoiding signal distortion. In order that the pickup and the sample should not be heated by the current passing in the winding, the current was limited to 20 mA. Control experiments with a thermocouple placed in the sample showed that in practice the current may reach 30 mA without any heating effects. Over the pressure range of interest the variation in pickup resistance is not larger than several ohms, the total resistance of the pickup circuit amounting to several kilohms. It can be easily shown that the signal in this case is proportional to the applied load, and therefore processing of the measurement results is simple and convenient. The second beam of the oscillograph with time marks is used as a time scale, and it also fixes the moment of the explosive transformation by an electrical conductivity technique /23/ (the ionized decomposition products short-circuit the rollers, to which a potential difference is applied; the moment of short-circuiting is recorded by means of a simple electric circuit (Figure 6)). The oscillograph is triggered by closing a specially mounted contact with the aid of a falling weight. Typical oscilloscope traces of pressure pulses are shown in Figure 7.

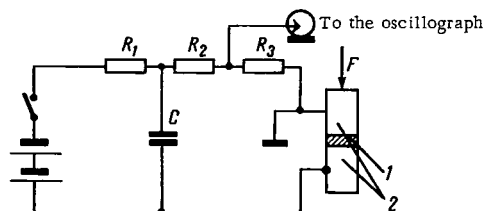


FIGURE 6. Electric circuit for fixing the moment of explosion, when the explosion products short-circuit the rollers:

1 — charge; 2 — rollers.

Mechanics of impact without explosive

Khariton /13/ compared the impact time ($\approx 10^{-3}$ sec) with the duration of sound-wave propagation throughout the rollers, i.e., the time for the stresses to balance ($\sim 10^{-6}$ sec), and he concluded that compression under impact may be regarded as a static process. Hertz' impact theory /62/ is based on this approach and is valid for impact velocities far below the velocity of sound. The velocity of the load is of the order of 1–5 m/sec, under the impact of a fall-hammer test, whereas the velocity of sound in steel is $c = 5000$ m/sec. Thus, the compression of the rollers due to the incident load is similar to the compression of a spring. If we consider an ideal case in which the striker is flat and only the rollers are

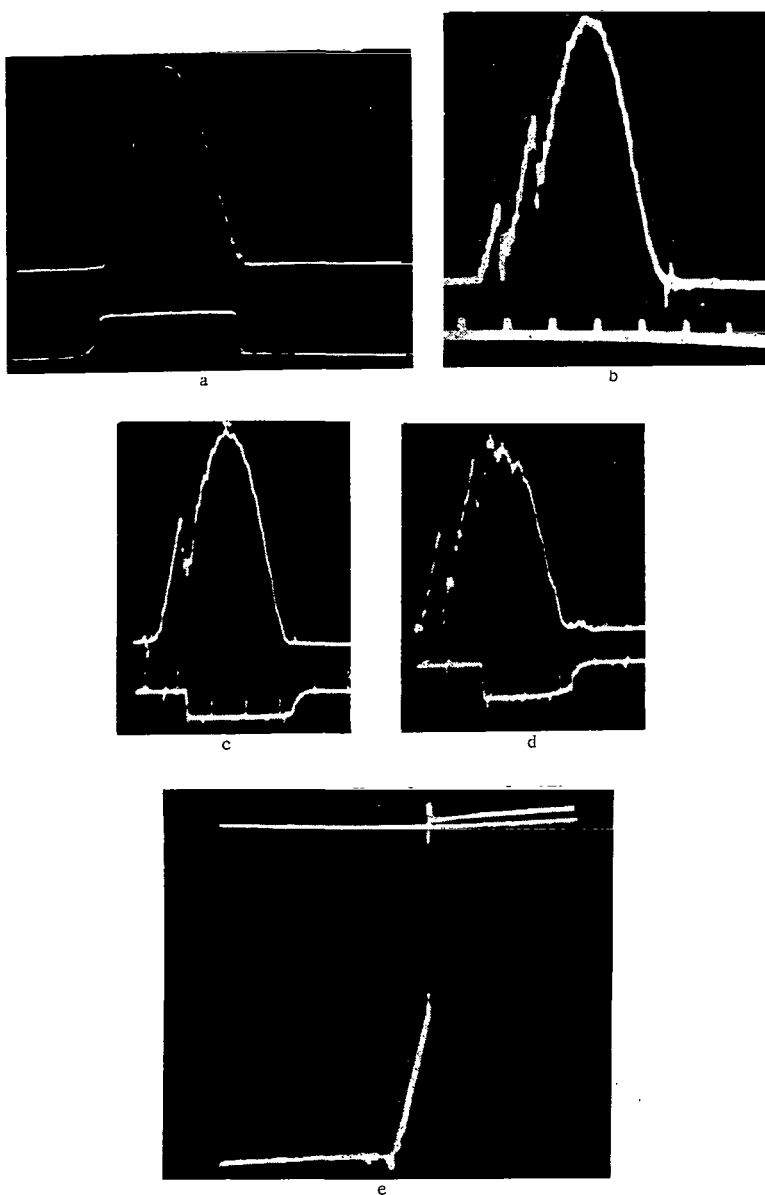


FIGURE 7. Typical oscilloscope traces of pressure pulses:

a — impact without explosive; b, c, d, e — impacts with explosive; b — no explosion;
c, d — explosion, e — explosion (lead azide and mercury fulminate).

compressed, and this within the elastic limit, then, by elementary methods involving Hooke's law and the equation of harmonic oscillations, the maximum pressure P_m and the impact time τ_{im} are given by

$$P_m = \sqrt{\frac{2WE'_M}{Sl}},$$

$$\tau_{im} = \pi \sqrt{\frac{Mt}{E'_M S}}. \quad (12)$$

Relationships (12) qualitatively reflect the dependence of the maximum fall-hammer impact pressure and the impact time on the load of mass M and

of kinetic energy W (impact energy), on the elastic properties of the rollers (E'_M is the Young modulus) and on their dimensions (l is the total length of the rollers and S is the cross-section area). The expression for P_m was obtained from the condition that all the impact energy W transforms into elastic energy of the rollers. The energy of elastic oscillations, which may arise upon impact, was not taken into account, since it is negligibly small and amounts to $0.02 u_0/c$ of the impact energy (u_0 is the velocity of the load) /63/.

The oscilloscope traces without explosive (Figure 7a) are similar in form to the half-period of a sinusoid, as expected for a static impact. The traces are analyzed in Figure 8. When the maximum pressure is attained (at time t_1), the load velocity vanishes.

The law of conservation of momentum yields

$$Mu_0 = \int_{\tau_0}^{t_1} S\bar{P}(t) dt,$$

where $S\bar{P}$ is the variation in the force from the beginning of the impact τ_0 until the load comes to rest at time t_1 , as recorded by the oscilloscope.

By an optical method described below, it was established that the load velocity in a K-44-2 fall hammer upon collision corresponds to free fall, and therefore

$$M\sqrt{2gH_0} = S \int_{\tau_0}^{t_1} \bar{P}(t) dt,$$

where H_0 is the fall height; $\bar{P}(t)$ is the varying pressure.

The value of the integral is found graphically from the oscillogram, the equation itself serving as a normalization condition. The error in the

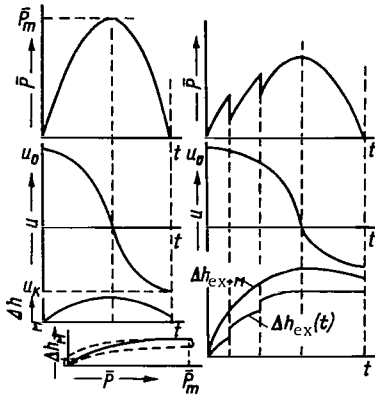


FIGURE 8. Interpretation of oscilloscope traces of pressure pulses.

pressure measurement amounts to 10% (both in the calibration on the press and on the fall hammer). Upon impact it consists of a calibration error (7%) and an error in the measurement of the oscillograph's beam deflection (3%). Figure 9 gives the dependence of the maximum pressure P_m on the impact energy W (for a K-44-2 fall hammer, and 10 and 5 kg loads).

By successive graphic integration of function $\bar{P}(t)$ in the oscillogram (Figure 8) the curve of the load velocity $u(t)$ is constructed, where

$$u(t) = u_0 - \frac{S}{M} \int_0^t \bar{P}(t) dt.$$

Having determined the variation in the kinetic energy of the load, $\Delta W = \frac{M}{2} (u_0^2 - u^2)$, and using the initial pressure oscillogram, one may now plot $\bar{P} = \varphi(\Delta W)$. The many traces show that $\bar{P} = \varphi(\Delta W)$ is independent of the fall height of the load, and of the load mass, and is in complete agreement with the dependence of the maximum pressure on impact energy (Figure 9). Hence the pressure upon an impact without explosive is independent of the rate of load application and is determined by the energy spent on deformation. This could not have been foreseen, since the fall-hammer impact is not completely elastic. Processing of the oscillogram indicates that about 20% of the impact energy is spent on plastic deformation of the metal of the rollers (and the bedplate) during the first stage of the impact (up to time t_1), and that the second stage of the impact (after time t_1) is completely elastic. Energy losses due to the plastic deformation of the metal constitute one of the causes of the weaker (by 12–15%) experimental variation of $\bar{P}_m = \varphi(W)$ as compared with that of formula (12).

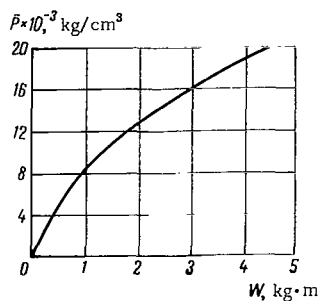


FIGURE 9. Maximum pressure upon an impact without explosive vs. impact energy.

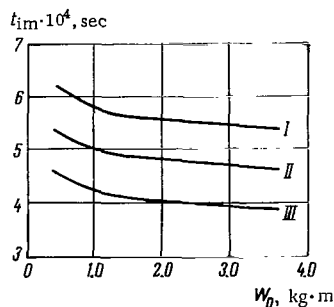


FIGURE 10. Impact time vs. impact energy:

I — K-44-2 fall hammer, 10 kg load; II — Kast fall hammer, 10 kg load; III — K-44-2 fall hammer, 5 kg load.

Graphical integration of the velocity $u(t)$ yields the displacement in time of the center of gravity of the load, $\Delta h_M = \Delta h_M(t)$, which occurs due to the compression of the metal parts, mainly of the rollers and of the striker. Elimination of time t between functions $\bar{P} = \bar{P}(t)$ and $\Delta h_M = \Delta h_M(t)$ determines the dependence of the metal compression on pressure: $\Delta h_M = \Delta h_M(\bar{P})$. This relationship can also be obtained from $\bar{P}_m = \varphi(W)$ using the differential relation $\bar{P}S = dW/dh$. The curves $\Delta h_M = \Delta h_M(\bar{P})$ are presented in Figure 8: solid curve for loading (up to time t_1) and dashed curves for unloading (after time t_1). The dependence $\Delta h_M = \Delta h_M(\bar{P})$ reflects the geometry of the collision and the material of the compressed elements.

The K-44-2 fall hammer has a spherical striker ($R = 50$ mm) and localized deformation takes place in the contact zone. The nonlinear character of $\Delta h_M = \Delta h_M(\bar{P})$ is due to very considerable localized deformations, which probably occur at the bedplate—roller, roller—roller, and in the first place load—roller interfaces, and constitutes another cause of the departure of the experimental dependence $\bar{P}_m = \varphi(W)$ from formula (12).

According to expression (12), the impact time does not depend on the fall height H_0 of the load. In experiments, however, there is a decrease in impact with increasing fall height (Figure 10) due to the nonlinearity of $\Delta h_M = \Delta h_M(\bar{P})$ and the incomplete elasticity of the impact. The dependence $\Delta h_M = \Delta h_M(\bar{P})$ or $\bar{P}_m = \varphi(W)$ uniquely determines the loading conditions in the case of impact without explosive and may therefore be taken as a characterization of the fall hammer and instrument. The Kast and K-44-2 fall hammers differ considerably from one another, as is evident from the dependences of the impact time on fall height of the load (Figure 10).

Mechanics of impact with explosive

The pressure oscillograms upon impact (Figure 7b, c and d) enable one to calculate the deformation curve of the explosive charge upon impact loading. Two successive graphic integrations (Figure 8) (as in the case of impact without explosive) yield the time-displacement $\Delta h_{M+ex} = \Delta h_{M+ex}(t)$ of the center of gravity of the load. In this case, however, it constitutes the sum of the compression of the metal and of the thickness variation of the sample deformed in the impact process. To isolate the sample deformation $\Delta h = \Delta h(t)$ from the total displacement, it is necessary to subtract the compression of the metal for known pressure $\bar{P} = \bar{P}(t)$ and dependence $\Delta h_M = \Delta h_M(\bar{P})$. For pressure increase, the loading curve is used, and for pressure decrease the unloading curve is used.

The sharp variations in \bar{P} and Δh at some moments (the resolving power of our photography was 5—10 μ sec and these variations are recorded as instantaneous) correspond to the fracture of the sample and the ejection of some of the material from the compression region. To determine the nature of sample fracture upon impact we tested a number of explosives (TNT, Teteryl, both dispersed and single-crystal compactness RDX, PETN, oktogen,* etc.), ballistite N, RDX + 9% liquid addition of the paraffin type, ground chalk and chalk containing various percentages of paraffin (3, 5, 10 and 15%; the paraffin was introduced by the same method as that used in the desensitization of an explosive), sodium nitrate, barium nitrate, ammonium perchlorate, lead, cellulose (paper) and others.

* [Russian brand name of explosive.]

Several fracture mechanisms can be assumed: 1) loss of stability of a free-flowing medium; 2) sharp decrease in viscosity, as occurs for rigid structures under high stresses and straining rates; 3) fracture of the sample upon reaching the ultimate strength at the slip planes. Fracture occurs in all systems which have not been prestressed, except ground chalk, chalk with paraffin, and lead. In addition, the fracture pressure is higher the stronger the material. On this basis the fracture may be assumed to be of the tensile type /64/. Pressure drops are also absent in elastic polymers (rubber, Thiokol).

Depending on the relative rate of straining and sample thickness, ballistites behave in a double manner: they are brittlely fractured after elastic deformation, or undergo elastic and then viscoplastic deformation (in the latter case smooth pressure oscillograms are obtained). The behavior of ballistic powders is in good agreement with the concepts of the mechanical properties of linear polymers /65/. Part of the described data on the behavior of various materials under fall-hammer impact will be used when discussing the works of other authors.

If explosion occurs, there is a sharp drop on the pressure oscillogram (Figure 7c and d). The question then arises as to whether the explosion

and the following rapid expansion of the explosion products cause the pressure drop, or whether the explosion occurs during the drop.

Figure 7e shows a typical pressure recording, obtained from the explosion of lead azide and mercury fulminate /66/. These initiating explosives detonate and destroy the rollers, including the pickup. Breaking the circuit is equivalent to an infinite increase in the resistance, so the oscillograph beam leaves the scale without even the smallest pressure drop being observed (in these experiments the beam brightness was intentionally increased). Hence it is clear that the explosion occurs before the pressure drop, the drop resulting from the explosion.

Returning to the interpretation of the oscillograms, we note that by eliminating time from the dependences $\bar{P} = \bar{P}(t)$ and $\Delta h = \Delta h(t)$ one may obtain the pressure-displacement ($\bar{P}-\Delta h$) diagram and the ($\bar{P}-\epsilon$) pressure-deformation diagram, which characterize the deformation process and the mechanical properties of the sample (Figure 11). The discontinuities on these diagrams correspond to the ejection upon fracture of part of the charge from the region of compression.

Figure 11 consists of two graphs, (a) and (b). Graph (a) is a pressure-displacement diagram with the y-axis labeled $\bar{P} \cdot 10^{-3} \text{ kg/cm}^2$ ranging from 0 to 8 and the x-axis labeled $h_0, \text{ mm}$ ranging from 0 to 0.6. It shows three curves with sharp vertical drops at approximately 0.1, 0.4, and 0.6 mm. Graph (b) is a pressure-deformation diagram with the y-axis labeled $\bar{P} \cdot 10^{-3} \text{ kg/cm}^2$ ranging from 0 to 8 and the x-axis labeled ϵ ranging from 0 to 0.8. It shows three curves with sharp vertical drops at approximately 0.1, 0.4, and 0.8. Both graphs show data points as 'x' marks connected by lines.

FIGURE 11. Typical pressure—displacement (a) and pressure—deformation (b) diagrams.

Optical method of measuring displacements

To check the computed values of $\Delta h = \Delta h(t)$, in conjunction with Zhuchenko /66/ we developed an optical method of recording displacements using a

ZhFR-2 driven photorecorder. The optical layout is shown in Figure 12. The upper roller (3) of the stamping machine is illuminated through condenser (2) by a pulsed (IFK-20) light source (1). The light is reflected from the roller, passes through lenses (4), (6), and slit (5) situated at the conjugate foci of these lenses, and is incident on rotating mirror (7) and then on photographic film (8). By means of an "Industar-51" objective and a specially prepared 56.5-cm-long tube the photography scale was increased by a factor of 13; when processing the results, this yielded a measurement accuracy of not less than 0.02 mm. Since the object of the photography is the lateral surface of the upper roller, a sectorial cut of angle $90-120^\circ$ was made in the connector sleeve and bedplate of the stamping machine. A special white enamel with high reflectivity (albedo about 0.9) and good adhesion to the metal of the roller was coated on the lateral surface of the roller. Above this (approximately 1 mm from the lower end of the upper roller) a small strip of mat black paint with a high absorption coefficient (approximately 0.99) was painted. Upon impact, the boundary of the black and white fields moves together with the roller and records the vertical movement of the latter on the film, which is very sensitive. The illumination and the impact were synchronized in the same way as the triggering of the oscillograph. Simultaneous use of the optical method and the tensometric method of pressure measurement confirmed the accuracy of the computed $P - \Delta h$ diagrams and directly showed the ejection of material at the instant of the pressure drop.

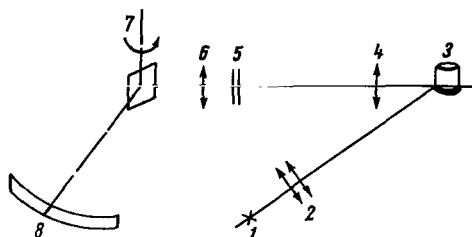


FIGURE 12. Optical layout for measuring displacements upon impact:

1 — flash lamp; 2 — condenser; 3 — moving roller;
4, 6 — lenses; 5 — slit, 7 — rotating mirror; 8 — photographic film

The optical method was used in /66/ to obtain additional data on the interesting effect of the sharp rise in explosion frequency in the case of liquid and initiating explosives for an elevated upper roller /67/. It was found that in this case the oncoming load imparts to the roller a speed equal to twice the speed of the load; the roller then collides with the explosive charge and recoils toward the falling load, and so on. A drop of liquid explosive is then sprayed, and the main impact already occurs with an explosive which incompletely wets the roller. This is similar to Bowden's experiments /19/ with charges in the form of strips and a multitude of droplets, when 100% explosions were recorded (according to Bowden,

these were due to adiabatic compression of gaseous inclusions). Upon impact with the solid explosive charge in instrument No. 2, an elevated roller effect is not observed. This effect appears in instrument No. 4 for initiating explosives when the charge is situated at the center. In this case the charge breaks down into individual pieces with a resulting change in ratio h/D which, as we assumed above and shall see below, is significant.

Deformation work of the charge

The area beneath the $\bar{P}-\Delta h$ curves (see Figure 11a) is determined by the energy absorbed by the charge upon impact. In the literature on sensitivity this quantity was accorded great importance, since a correspondence was assumed between the energy spent on deformation and the hot-spot temperature. Various methods were proposed for its determination (from the total energy of the impact /68/, from the total energy lost upon impact /69/, from the difference between the recovery energies in impacts with and without explosive /70/). Kholevo critically examined these methods and determined the work W_{ex} done on the charge upon impact using the relationship

$$W_{ex} = Mg \left(H_0 - \frac{1}{e} H_1 \right), \quad (13)$$

where H_0 is the fall height of the load; H_1 is the height of recoil; e is the coefficient of restitution of the fall hammer.

On the basis of the obtained $\bar{P}-\Delta h$ diagrams we consider questions of energy losses during impact and show the applicability limits of (13).

For an impact without explosive (Figure 7a), the energy W_0 of the falling load is spent on elastic and plastic deformation of the metal. The elastic fraction W_M^{el} of the energy is realized upon the recoil of the load, and for most fall hammers amounts to 0.6–0.8 of the impact energy. The optical method was used to measure the speed of the load upon recoil. It was found to be above the value $u_1 = \sqrt{2gH_1}$ for a free-fall calculation, apparently due to sliding of the load stop on the fixing bar. Experiments showed that the following relationship is well satisfied:

$$MgH_1 = \gamma W_M^{el}, \quad (14)$$

where γ is a coefficient allowing for the sliding of the stop and amounting to approximately 0.9, for our (K-44-2) fall hammer with a 10-kg load. For an impact without explosive the energy balance is given as follows:

$$W_0 = W_M^{pl} + W_M^{el}$$

or

$$MgH_0 = W_M^{pl} + \frac{1}{\gamma} MgH_1, \quad (15)$$

where W_M^{pl} is the energy spent on plastic deformation of the metal.

If for each fall height H_0 the recoil height H_1 occurs fairly often, then W_M^{pl} is also constant for each H_0 . In the case of impact on cold-hardened rollers the relationship $H_1 = eH_0$ (e being the coefficient of restitution of the fall hammer) is well satisfied. Together with expressions (14) and (15) this yields

$$W_M^{pl} = \left(\frac{\gamma}{e} - 1 \right) W_M^{el}, \quad (16)$$

i.e., in the case of impact on cold-hardened rollers the work spent by the load on irreversible deformation of the metal elements of the machine is proportional to the elastic part of the impact energy (for our fall hammer and rollers $e = 0.73$).

For impact with explosive (see Figure 7b, c, and d) some of the impact energy is expended on plastic and elastic deformation of the metal, the remaining part W_{ex} being expended on elastic and inelastic deformation of the charge. At the instant of sharp pressure drop and ejection of some of the explosive from the compression region, estimates show that the pressure on the rollers drops from \bar{P}_i to \bar{P}_j and they lose irreversibly a part W_c of the stored elastic energy, which is dissipated in the form of sound waves throughout the machine components. We shall refer to this as seismic losses, the value of which is given by

$$W_s = \sum_n \frac{e}{\gamma} [W(\bar{P}_i) - W(\bar{P}_j)],$$

where n is the number of pressure drops, and the values of $W(\bar{P}_i)$ and $W(\bar{P}_j)$ are taken from the experimental dependence $\bar{P}_m = \varphi(W)$, presented in Figure 9. With the aid of formula (12) we have

$$W_s = \frac{Sl}{2E_M} \sum_n (\bar{P}_i^2 - \bar{P}_j^2).$$

The quantity W_{ex} , the fraction of the impact energy expended on elastic and inelastic deformation of the charge, is determined by the area beneath the $\bar{P}-\Delta h$ diagrams. The elastic energy accumulated by the charge transforms upon decomposition (partially) into kinetic energy of the ejected explosive (at instants of pressure drops the phenomenon has a wave and not a static character). Thus, the energy balance for impact with explosive is

$$W_0 = W_M^{pl} + W_M^{el} + W_s + W_{ex}.$$

Using expressions (14) and (16) and transforming to fall and recoil heights, we have

$$W_{ex} = Mg \left(H_0 - \frac{1}{e} H_1 \right) - W_s. \quad (17)$$

Table 1 illustrates the energy balance upon impact (K-44-2 fall hammer, 10-kg load, instrument No. 2, charge mass 0.050 g).

For low impact energies the maximum pressure is also small and does not reach the tensile strength of the sample, the pressure oscillograms are

close in form to those of impact without explosive, there are no sharp pressure drops and therefore $W_S = 0$. Sharp pressure drops may be absent for ballistic powders and lead, and are absent for elastic polymers, in which cases also $W_S = 0$. Thus, it follows from (17) that (13) is satisfied for smooth oscilloscope traces of pressure pulses.

TABLE 1. Energy balance (in kg·m) for impact on 50-mg explosive charges

Explosive	w_0	w_{ex}	w_S	w_M^{pl}	w_M^{el}
RDX	0.50	0.14	0	0.07	0.27
	0.50	0.12	0	0.08	0.28
	1.00	0.20	0.52	0.11	0.15
	1.00	0.18	0.51	0.12	0.21
	1.50	0.22	0.60	0.21	0.44
	1.50	0.21	0.42	0.28	0.61
	2.00	0.25	0.54	0.24	1.07
PETN	0.50	0.16	0	0.09	0.28
	0.50	0.17	0.18	0.05	0.11
	1.00	0.24	0.32	0.14	0.34
	1.00	0.20	0.39	0.15	0.31
	1.50	0.17	0.46	0.25	0.62
	1.50	0.18	0.40	0.21	0.77
RDX + 9% liquid addition of a paraffin type	1.00	0.23	0.36	0.11	0.30
	1.00	0.19	0.18	0.16	0.49
	1.50	0.16	0.60	0.20	0.57
	1.50	0.23	0.51	0.19	0.68
	2.00	0.27	0.50	0.26	0.95
	2.00	0.34	0.71	0.23	0.80

This table shows how small a fraction of the impact energy is represented by the energy expended on deformation of the charge. If it all transformed into heat, the charge would heat up by an amount of the order of 10°C. Nevertheless, this energy is approximately a billion times as high as the energy required to form a 10^{-4} cm hot spot possessing the critical temperature.

We note in this connection that the total deformation work of the charge has been separated into elastic W_{ex}^{el} and inelastic W_{ex}^{pl} parts. If we estimate W_{ex}^{el} by the formula

$$W_{ex}^{el} = \frac{\bar{P}_{ten}^2 Sh}{2\kappa}$$

(where κ is the bulk modulus of compression), we obtain values of the same order as the measured ones (for a pressed-charge thickness of $h \approx 0.4$ mm, corresponding to 0.050 g, for RDX $\bar{P}_{ten} = 4800$ kg/cm²; the bulk modulus of compression for RDX is $1.1 \cdot 10^5$ kg/cm² /71/). Hence it follows that W_{ex}^{pl} is either of the same order of magnitude, or is smaller than W_{ex}^{el} .

Mechanical properties of solid explosives

The experiments were carried out in instrument No. 2. Many explosives (TNT, trinitrophenol, Tetryl, ammonium nitrate, PETN, RDX, oktogen, tetrazene, TNRS, lead azide, mercury fulminate, etc.) and some inert materials of various sample thicknesses were tested. The computed pressure-deformation ($\bar{P}-\varepsilon$) diagrams for all these materials are close in form to that shown in Figure 11b (ε is the relative deformation of the sample). If the first pressure drop is caused by the explosion of the charge, then in this case the diagram has a similar form to the first section (up to the first disintegration) of the same diagram (Figure 11b). These diagrams characterize solid explosives as a strongly consolidated medium (close to elastic) which undergoes a very small deformation (less than 10%) before fracture. Therefore, considering only the first pressure drop on the oscillogram, one can to a good approximation take the thickness at which explosion occurred as the initial thickness of the charge. This however is true only for pressed charges. The point is that between a solid explosive charge and the rollers there are always fairly small gaps which do not allow a simultaneous impact everywhere. Pressed charges are insensitive to impact by the roller, whereas fractional charges are partially scattered (the air situated in the pores probably also helps in the scattering). Comparison of computed displacements Δh during impact with differences in the initial and final sample thicknesses gives agreement for pressed samples and disagreement for fractional samples. The differences sometimes reach 40% of the initial thickness, namely, as if the impact occurred with a thinner charge. As a result only pressed charges were considered in the following.

TABLE 2. Average values of measured \bar{P}_{ten} and \bar{P}_{ex} (marked by an asterisk) in thousands of atm for various-charge heights

Explosive	Charge height h , mm ($D=10$ mm)												
	1.00	0.90	0.80	0.70	0.60	0.50	0.40	0.35	0.30	0.25	0.20	0.15	0.10
TNT	0.85	—	1.1	—	1.4	1.7	2.1	—	2.65	2.65	3.7	5.1	7.2
Trinitrophenol	1.5	—	1.6	—	2.2	2.7	2.9	—	4.1	—	5.7	6.5	9.7*
Tetryl	1.35	—	1.6	1.9	2.0	2.5	3.3	—	4.15	4.4	5.8	7.0	9.9*
PETN	1.7	—	2.1	2.1	2.6	3.1	3.5	3.8	4.6	5.2*	6.0*	8.1*	—
RDX	2.2	2.5	2.6	3.2	3.2	4.0	4.65	—	6.1	7.1*	8.9*	11.1*	—
Oktogen	3.25	3.65	3.7	4.5	4.75	5.55	6.4*	7.7*	8.2*	9.4*	11.2*	—	—

Table 2 and Figures 13 and 14 present for a number of explosives the experimentally measured pressures under which fracture occurs (\bar{P}_{ult}) or an explosion is recorded (\bar{P}_{ex}). The experiments were carried out in instrument No. 2 ($D=10$ mm) for various initial charge thicknesses. The pressing pressure was 5–20,000 atm, and in most cases was so chosen as to approximately exceed \bar{P}_{ult} or \bar{P}_{ex} by a factor of two. The charge density was in this case approximately 10% lower than that of a single crystal. Each value in the table (and the corresponding point on the graphs) is the averaged value of the measured quantity over not less than 10 experiments. First it

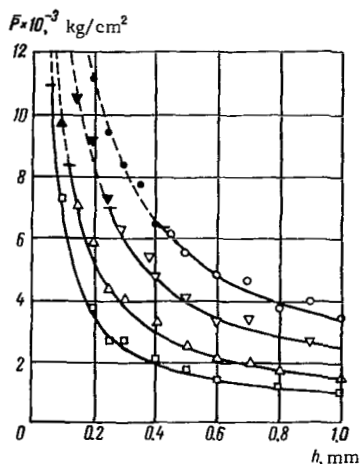


FIGURE 13. Average pressures upon fracture (P_{ult} —solid curves) and upon explosion (P_{ex} —dashed curves) vs. charge thickness of oktozen (\bigcirc), RDX (∇), Teteryl (\triangle) and TNT (\square).

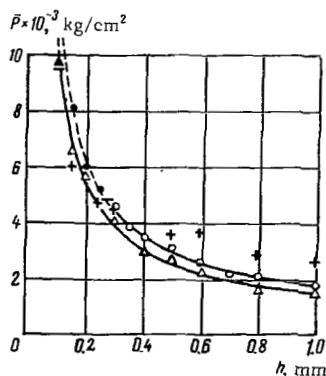


FIGURE 14. Average pressures P_{ult} and P_{ex} vs. charge thickness for PETN (\bigcirc) and trinitrophenol (\triangle). Points marked + refer to dina.

was necessary to study how these averaged values are affected by the degree of dispersion of the explosive, the pressing pressure, and the speed of the load upon impact.

The influence of the degree of dispersion was studied in the cases of PETN, RDX, and oktozen. Various fractions with grain sizes from 1–10 to 315–400 μ were tested. The average values of \bar{P}_{ult} and \bar{P}_{ex} within the experimental error (10%) were found not to depend on the degree of dispersion of the explosive. The same values are also obtained both for pressed samples and for samples of single-crystal density. For explosives difficult to press the degree of dispersion affects the spread of the measured quantities about their average value. With decreasing grain size the spread slightly decreases, as also does the spread with respect to the thickness of the pressed charges. This apparently is due to the improved homogeneity of the samples. Therefore explosives difficult to press (PETN, RDX, oktozen) were used in the form of finely deposited fractions (1–10 μ).

Within the measurement error for a given situation, the average values of \bar{P}_{ult} and \bar{P}_{ex} for explosives of various degrees of dispersion are also independent of the charge pressing pressure when the latter exceeds 200 atm (for lower values some of the charge is scattered because the impact is not simultaneous everywhere). With increasing pressing pressure, the spread of the resulting data slightly decreases, apparently due to the improved sample homogeneity. If the pressing pressure is less than the value being measured, then the effect upon impact is as though there is additional pressing of the charge, and this shows up by increasing the deformation of the charge just before fracture relative to well pressed charges. Serial measurements were therefore performed on samples pressed to higher pressures than the value being measured. If the charge density after pressing was more than 10% lower than the proper density of the explosive,

such charges were rejected. The speed of the impact too does not influence the average values of the measured \bar{P}_{ult} and \bar{P}_{ex} . The influence of the speed was studied in the cases of PETN and RDX. Very careful measurements involving the many different speeds allowed by the K-44-2 fall hammer were performed using RDX: in measuring \bar{P}_{ult} and \bar{P}_{ex} the load speed varied by factors of 4.5 (fall heights of 5 and 100 cm) and 2.6 (fall heights of 15 and 100 cm) respectively. The results do not differ by more than the 10% measurement error. Table 2 and Figures 13 and 14 were obtained for a 10-kg load drop height of 25 cm.

The individual experimental fracture pressures \bar{P}_{ult} obtained as a function of the initial charge height (see Table 2) can be represented to within the measurement error by hyperbolic relationship (10):

$$\bar{P}_{ult} = \sigma_{ult} \left(1 + \frac{D}{3\sqrt{3}h} \right). \quad (18)$$

Thus, if $0.01 \leq h/D \leq 0.10$ this formula is experimentally confirmed also for brittle systems under compression by impact (with the exception of dina). The measurement data and formula (18) enable the ultimate strength σ_{ult} to be found. Values of σ_{ult} averaged over all the experiments are given for various materials in Table 3. Figures 13 and 14 were plotted using these average values and formula (18). (Above we spoke everywhere of the average values of the measured \bar{P}_{ult} and \bar{P}_{ex} . The spread of the data about these average values is fairly large, amounting to $\pm 25\%$, which is larger than the measurement error. To illustrate the spread, Figure 15 presents data of individual measurements for RDX, the average values for which are given in Table 2 and Figure 15.)

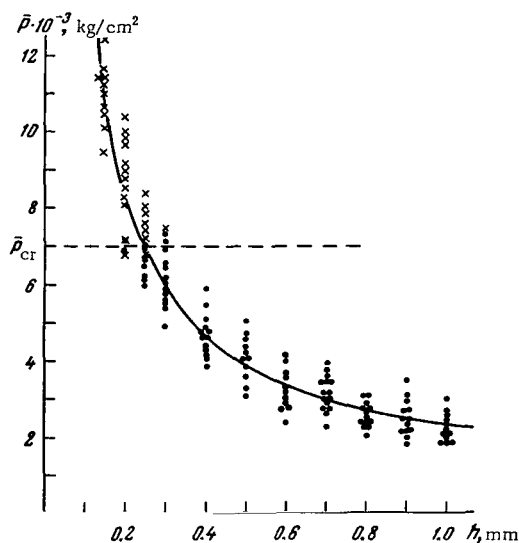


FIGURE 15. Spread of the measured pressures upon fracture (P_{ult} — the points) and upon explosion (P_{ex} — the crosses) for RDX.

TABLE 3. Melting temperatures and effective ultimate strengths for various materials

Explosive	$T_{\text{mel}}, ^\circ\text{C}$	$\sigma_{\text{ult}}, \text{kg/cm}^2$
Diphenylamine	52.9	190
TNT-Tetryl eutectic	68.8	290
TNT	81	340
Trinitrophenol	121.9	520
Tetryl	131	530
PETN	141	600
Ammonium nitrate	169.6	650
RDX	201	820
Oktogen	280	1250
NaNO_3	308	1430
$\text{Ba}(\text{NO}_3)_2$	592	2300

The resulting values of σ_{ult} are the effective ultimate strengths of the explosives as polycrystalline bodies (the strength of single crystals possesses an anisotropy). It is noteworthy that these values are 2–4 times as high as the ultimate strengths which are usually determined upon the compression of pressed charges ($h/D \geq 1$). Let us consider in this connection the transcrystalline and intercrystalline strengths for polycrystalline bodies, as distinguished in physical metallurgy [72]. The former is related to granular fracture and is determined by the strength of the grain material; the latter is related to the fracture of grain boundaries and is determined by their cohesion strength. Transcrystalline strength is the maximum possible strength of a polycrystalline body. Intercrystalline strength can only approach it (in the case of metals) but may in general be arbitrarily low, which is what one should expect for samples pressed from a powder of brittle nonplastic materials, such as solid explosives (owing to the low plasticity the grain boundaries do not close up).

For metals, the ultimate strength (for which the intercrystalline strength is responsible) is close to the compressive strength (for which both the intercrystalline and transcrystalline strengths are responsible). In pressed explosives, fracture under tension occurs at very low stresses (of the order of 10 kg/cm^2), whereas under compression, stresses of the order of 10^2 kg/cm^2 ($100\text{--}200 \text{ kg/cm}^2$) are required for fracture. These stresses can be increased, if the cohesion between the grains, and thereby the intercrystalline strength, are increased. Thus, for example, the compressive strength of explosive charges pressed together with a solvent is considerably increased.

The ultimate strengths σ_{ult} measured by us upon impact are indexes of the transcrystalline strength, i.e., of the proper strength of the explosive, since in the relevant problem of the deformation of a thin disk, fracture occurs when the ultimate shear strength τ_{ult} ($\tau_{\text{ult}} = \sigma_{\text{ult}}/\sqrt{3}$) of the disk material is reached over the whole contact surface.

We now consider other results regarding the mechanical properties of solid explosives which will be used in the following.

The effective ultimate strengths of a wide circle of explosives, eutectic explosive alloys and some inert materials were measured in cooperation with Karpukhin [66, 73]; within the measurement error they were linearly

dependent on their melting temperatures (see Table 3):

$$\sigma_{\text{ult}} = 4.2 T_{\text{mel}} \quad (19)$$

where T_{mel} is expressed in $^{\circ}\text{C}$ and σ_{ult} in kg/cm^2 . This dependence arises because both quantities are determined by the intermolecular interaction energy. However, relationship (19) is only a first approximation, since the mechanical characteristics may depend strongly, for example, on polymorphism, which is very widespread for explosives. In this connection dina is an exception, but, as mentioned above, it is also not represented by formula (18) (the average values of \bar{P}_{ult} for dina are shown in Figure 14).

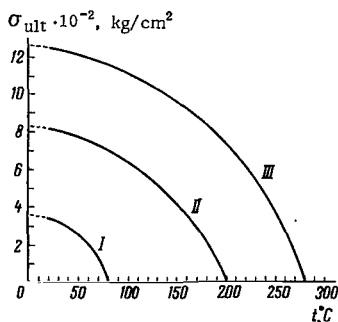


FIGURE 16. Ultimate strength vs. initial temperature for TNT (I), RDX (II) and oktozen (III).

The influence of the initial temperature on the ultimate strength was studied for oktozen, RDX, and TNT. The heating was controlled by a thermocouple placed in the sample. Dynamic heating was used to reduce possible decomposition of the explosive. Measurement of \bar{P}_{ult} was carried out for various sample thicknesses, after which σ_{ult} was found by formula (18). Figure 16, which shows the variation of the ultimate strength, implies that, as expected, it decreases with increasing temperature and vanishes at the melting point.

In physical metallurgy the variation of the mechanical properties is assumed to be associated with the variation of the relevant temperature T_0/T_{mel} (in $^{\circ}\text{K}$), assuming that for equal such temperatures one should expect the same mobility of the structural elements of the lattice or the same degree of thermal destruction of the crystal. Although in the case of metals this consideration is referred most to the variation of the plastic properties, it is well illustrated also by our measured values of σ_{ult} (both the decrease in strength with increasing initial temperature (see Figure 16) and the decrease in strength at normal temperature with decreasing melting temperature of the material are related to the decrease in the above relative temperature). In the theory of pressure treatment of metals /74/ it is assumed that for $T_0/T_{\text{mel}} > 0.4-0.5$ recrystallization plays a significant role in plastic deformation; for higher values of T_0/T_{mel} relaxation effects become increasingly

more noticeable. Deformation properties are described with the aid of a viscoplastic model for $T_0/T_{\text{mel}} > 0.7 - 0.8$ and of a viscous-liquid model for $T_0/T_{\text{mel}} > 0.8 - 0.9$. The given values of these temperatures refer to slow processes and are generally relative: increase with rate of straining, decrease with increasing degree of deformation. In any case, these values should be higher for impact loading. There is some analogy between solid explosives and what was said about metals. An examination of many pressure oscillograms and corresponding $\bar{P}-\varepsilon$ diagrams shows that as T_0/T_{mel} approaches unity, the pressure drops appear less sharp and the plasticity of the explosive increases. This is noticeable if the explosive has a relevant temperature $T_0/T_{\text{mel}} \gtrsim 0.9$. In conditions of slow loading, plasticity should appear for a lower limiting value of this temperature. It is known, for example, that the pressability of explosives improves with increasing temperature, and that at normal temperature low-fusible explosives such as TNT ($T_0/T_{\text{mel}} = 0.85$), Tetryl (0.75), and dina (0.91) can be well pressed and explosives whose melting temperature is above that of Tetryl as a rule cannot be well pressed (for poorly pressable PETN $T_0/T_{\text{mel}} = 0.72$).

Thus, under conditions of slow pressing the limiting value is tentatively $T_0/T_{\text{mel}} = 0.72 - 0.75$, whereas in the case of impact loading of thin layers plasticity is noticed when $T_0/T_{\text{mel}} \gtrsim 0.9$. This discussion of the mechanical properties as related to the value of the relative temperature touches only upon the general features of explosive behavior and its limits of applicability to different explosives are unclear (one should allow for the type of lattice, the type of bond, etc.). Nevertheless the general outline is valid, and possibly the unusual behavior of dina is somehow related to the high value of the relative temperature.

Pressure at which explosion occurs as a function of charge thickness

The experimentally obtained behavior of explosives (see Figures 13 and 14) on the whole agreed with the assumed one (Figure 4), except that the pressures \bar{P}_{ex} (the average values) at which explosion occurs are situated not in a zone, but within the measurement error on the strength curve. The pressure at which transition occurs from fracture to explosion is naturally associated with the critical stress \bar{P}_{cr} in instrument No. 2. Table 4 gives the measured values of \bar{P}_{cr} and h_{cr} (the charge thickness at which fracture changes to explosion). The values of \bar{P}_{cr} and h_{cr} are determined more accurately by increasing the number of experiments in this transition region. As an example, Figure 17 presents the results of such measurements for RDX. The horizontal line indicates the value chosen for \bar{P}_{cr} . The deviation of explosions (below) and fracture (above) from this line is fairly small (up to 15%). The strength curve is taken from Figure 15.

The experiments showed that, within the measurement error, \bar{P}_{cr} thus determined is independent of the charge pressing pressure (for the same charge mass), of the degree of dispersion of the explosive, and of the load velocity upon impact. To illustrate the independence of \bar{P}_{cr} on the velocity,

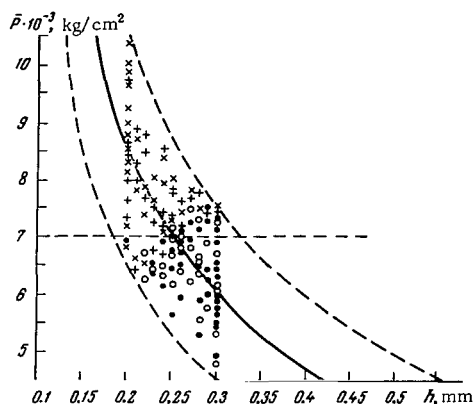


FIGURE 17. Spread of the measurement results in the RDX fracture-to-explosion transition region for two impact velocities:
2.2 m/sec: $\bullet - \bar{P}_{ult}$, $\times - \bar{P}_{ex}$; 4.4 m/sec: $\circ - \bar{P}_{ult}$, $+$ \bar{P}_{ex} .

Figure 17 presents measurement data for impact velocities of 2.2 m/sec ($H_0 = 25$ cm) and 4.5 m/sec ($H_0 = 100$ cm).

The spread indicates that the accuracy of the values in Table 4 is close to $\pm 10\%$. The "approximately" sign appears for those explosives with small h_{cr} , for which measurements are difficult (such thin layers cannot be pressed) and the accuracy is lower.

TABLE 4. Critical stresses in instrument No. 2 for various explosives

Explosive	$\bar{P}_{cr} \cdot 10^{-3}, \text{ kg/cm}^2$	$h_{cr}, \text{ mm}$
TNT	~ 11	~ 0.08
Trinitrophenol	~ 9.5	~ 0.11
Tetryl	~ 8.4	~ 0.12
RDX	7.0	0.25
Oktogen	6.4	0.43
PETN	4.8	0.27

The form of oscillograms obtained for various charge thicknesses is as follows. For $h < h_{cr}$ the recording has the form shown in Figure 7c, if the impact energy is such that pressures exceeding the tensile strength are attained; otherwise the oscillogram has the same form as in an impact without explosive (see Figure 7a). If $h > h_{cr}$, two types of oscillogram may occur (see Figure 7b and d). The possibility of an explosion depends on whether the remaining charge thickness is less than h_{cr} after fracture (or several fractures) and ejection of part of the material. If the thickness is less than the critical value, the possibility of an explosion depends on whether the remaining impact energy (after seismic and other losses) is sufficient to exceed the ultimate strength.

What is termed a standard charge (0.050 g) corresponds in the pressed state for organic materials to a charge of thickness $h \approx 0.4$ mm. This

explains why under impact in an instrument with explosive ("standard" charge) a failure is recorded, while for repeated impact from the same height explosion occurs. In the first impact, the energy left after fracture (or several fractures) was insufficient for reaching the tensile strength of the residual layer. In the repeated impact, the energy again is high and the ultimate strength of the residual layer is attained.

For secondary explosives most of the charge thicknesses ($0.1 \text{ mm} \leq h \leq \leq 1.0 \text{ mm}$) for which measurements were performed are occupied by fractures, and TNT, for example, explodes only for very thin charges. On the other hand, initiating explosives explode over the whole range of values. The pressure oscillograms for tetrazene and TNRS always have the form shown in Figure 7c, whereas for lead azide and mercury fulminate they have the form shown in Figure 7d (due to the destruction of the pickup upon explosion). For lead azide and mercury fulminate oscillograms of the type shown in Figure 7c are obtainable, if sufficiently small charges are used and an intermediate roller (or two) are placed between the charge and the pickup, in which case upon explosion the intermediate roller is destroyed and the pickup remains intact. Average values of \bar{P}_{ex} as a function of charge thickness are given in Table 5 (the values of \bar{P}_{ex} are given in 10^3 atm).

It has been verified that these values are unaffected by the pressing pressure (for the same charge mass) and the low velocity upon impact. The influence of the degree of dispersion was not studied. The values of \bar{P}_{ex} obtained for initiating explosives, as for secondary explosives, fit well a hyperbolic dependence on h similar to (18):

$$\bar{P}_{\text{ex}} = C \left(1 + \frac{D}{3 \sqrt[3]{3} h} \right),$$

which is shown in Figure 18. The value of the constant C for each initiating explosive is also given in Table 5. By analogy with secondary explosives (see Figure 13), this constant could be interpreted as the ultimate strength. However, such a dependence may also involve the attainment of a stress which produces a definite (the same for different h/D) degree of deformation, since for a hardened body the stress has a one-to-one dependence on the deformation (monotonically increasing).

TABLE 5. Average pressures (in 10^3 atm) at which explosion occurs as a function of charge thickness (initiating explosives)

Explosive	Charge thickness h , mm										$C \cdot 10^{-3}$, kg/cm^2
	0.15	0.20	0.25	0.35	0.50	0.60	0.70	0.80	0.90	1.00	
Lead azide	—	17.0	—	9.8	6.9	—	5.6	—	5.1	5.0	1.55
TNRS	—	—	11.6	7.5	6.1	5.3	—	4.0	—	3.7	1.22
Tetrazene	10.2	—	7.1	4.8	3.6	3.4	—	2.4	2.2	2.2	0.75

As yet it is only possible to assert that the ultimate strength of initiating explosives is not less than the values obtained for the constant C . As regards the critical stress for these explosives in instrument No. 2, it should be

lower than the measured values of \bar{P}_{ex} (see Table 5), if this quantity exists at all (this problem is related to the melting temperature of initiating explosives).

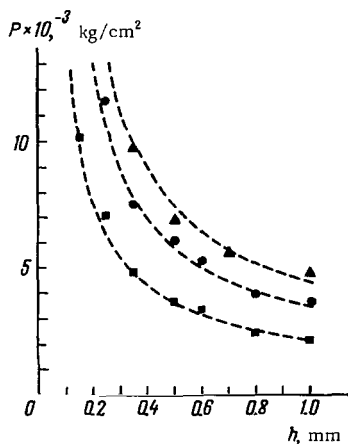


FIGURE 18. Average pressures at explosion vs. thickness for initiating explosives:

▲ — lead azide; ● — TNRS; ■ — tetrazene.

It was mentioned above that the experimentally obtained behavior of explosives on the whole agreed with the assumed one (at least for secondary explosives), except that values of \bar{P}_{ex} do not occupy a zone (see Figure 4), but coincide with the strength curve (see Figure 13). However, the assumed picture referred to the conditions for the formation of an effective hot spot, whereas the experimental picture is based on explosion data. Therefore any analogy between these "pictures" only exists when the real induction period is so small that under impact conditions the difference between the pressure when an effective hot spot formed and the pressure \bar{P}_{ex} under which this hot spot ignited may be neglected. Only in this case may the minimum value of \bar{P}_{ex} (denoted by $\bar{P}_{ex \min}$) be interpreted as \bar{P}_{cr} .

In the light of the above results we therefore discuss the induction period of an effective hot spot prior to explosion before investigating the factors which determine the initiation of explosion in instrument No. 2.

§4. Critical deformation conditions

Adiabatic induction period

The pressure oscillograms (see Figure 7c) give the delay time τ_d of the explosion from the beginning of the impact. In the case of a load dropping from a height of 25 cm and a sample thickness of $h \approx h_{cr}$ this time lasts approximately 100–200 μ sec for various explosives. By increasing the impact velocity, say by a factor of 2 ($H_0 = 100$ cm), the minimum pressure

$\bar{P}_{\text{ex min}} (h = h_{\text{cr}})$ required for an explosion does not vary (see Figure 17), and the delay time decreases to $50-100 \mu\text{sec}$. Consequently, in these cases the order of magnitude of the induction period does not exceed 10^{-4} sec.

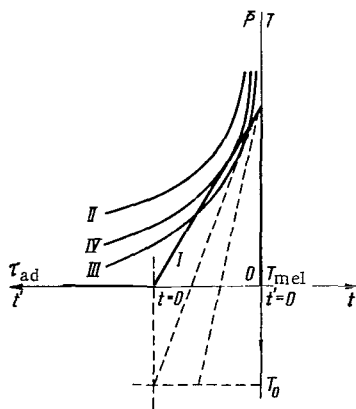


FIGURE 19. Beginning of the adiabatic induction period.

We shall attempt a more precise analysis with the aid of the pressure oscillogram for explosion (see Figure 7c). Under the transformation $t' = \tau_d - t$ (t being the old coordinate) explosion occurs at $t' = 0$, and the beginning of impact is at $t' = \tau_d$, i.e., we measure the time from explosion to the beginning of impact. Figure 19 (curve I) shows schematically in terms of the new coordinates the relevant part of the pressure oscillogram (from the beginning of impact to explosion at \bar{P}_{ex}). Now suppose for some pressure (for simplicity we will assume that the pressure over the whole roller is the same and equal to the average pressure \bar{P}) hot spots are created, the temperatures of which equal the melting temperature at this pressure, i.e., each value of \bar{P} corresponds to a definite temperature $T = T_{\text{mel}} = T_{\text{mel}}(\bar{P})$. This latter dependence is taken in the approximate form

$$T_{\text{mel}}(P) = T_{\text{mel}} + \alpha P.$$

In turn, to each temperature T there corresponds a definite adiabatic induction period τ_{ad} . The dependence of the adiabatic induction period on temperature is plotted in Figure 19. In principle three cases may occur: curve II does not intersect curve I, and so there cannot be explosion at $t' = 0$; curve III intersects curve I twice, and so explosion should have occurred before the instant when it actually occurred; and finally, the dependence of the adiabatic induction period on temperature, curve IV, intersects curve I once. This is the only plausible solution.

The condition for the curve $P = P(t')$ (curve I) to have a common tangent with $\tau_{\text{ad}} = \tau_{\text{ad}}(T)$ is

$$\begin{aligned}
T &= T_{\text{mel}} + \alpha P, \\
\tau_{\text{ad}} &= \frac{c\rho RT^2}{QEz} e^{\frac{E}{RT}}, \\
\tau_{\text{ad}} &= -(\bar{P}_{\text{ex}} - \bar{P}) \frac{dt'}{d\bar{P}}, \\
\alpha \frac{d\tau_{\text{ad}}}{dT} &= \frac{dt'}{d\bar{P}}.
\end{aligned} \tag{20}$$

These yield

$$\begin{aligned}
\frac{\bar{P}_{\text{ex}} - \bar{P}}{\bar{P}} &= \frac{RT^2}{E(T - T_{\text{mel}})}, \\
\tau_{\text{ad}} &= \frac{RT^2}{E(T - T_{\text{mel}})} \tau_{\text{d}}.
\end{aligned} \tag{21}$$

In obtaining this result the following two assumptions were made:

- 1) the pressure is uniform over the roller, i.e., $P = \bar{P}$;
- 2) the temperature of the hot spot under any pressure is equal to the corresponding melting temperature.

The first assumption is insignificant, since the result does not change if the true pressure at the spot rises proportionally to the average pressure, i.e., $P_{\text{true}} = k\bar{P}$ (k is a proportionality factor). The second assumption is obviously false, since according to it a hot spot (spots) of temperature equal to the normal melting temperature should have formed already at the beginning of the impact (the beginning of the deformation), i.e., an instantaneous heat-up from T_0 to T_{mel} should have occurred. We therefore replace this assumption by another, as follows. It is natural to assume that the heat-up increases with increasing deformation and stresses (and consequently also \bar{P}) and reaches the melting temperature only near \bar{P}_{ex} . The possible heat-up kinetics in this case are illustrated in Figure 19 by the dashed lines. For any of these lines $dT/dt' < \alpha d\bar{P}/dt'$ (in general, the proportionality of the temperature rise with decreasing t' is unessential; it is important only that this inequality be observed near \bar{P}_{ex}). It is now possible that curve IV, the adiabatic induction period versus temperature, may have curve I as a tangent, and that curve III intersects curve I, which lies above the point of tangency of $\tau_{\text{ad}} = \tau_{\text{ad}}(T)$ with the dashed lines. They all are taken into account by the following relationship:

$$\alpha \frac{d\tau}{dT} \geq \frac{dt'}{d\bar{P}}. \tag{22}$$

Replacing the last expression of system (20) by (22), we obtain finally

$$\begin{aligned}
\frac{\bar{P}_{\text{ex}} - \bar{P}}{\bar{P}} &\leq \frac{RT^2}{E(T - T_{\text{mel}})}, \\
\tau_{\text{ad}} &\leq \frac{RT^2}{E(T - T_{\text{mel}})} \tau_{\text{d}}.
\end{aligned} \tag{23}$$

It should be emphasized that this result holds irrespective of whether the temperature rise occurs at the same hot spot, or whether at each subsequent

moment new spots of higher temperature form. The obtained result refers to all explosions, both to \bar{P}_{ex} and to $\bar{P}_{\text{ex min}}$. Explosion, as we know, occurs if a temperature not less than critical is attained, i.e., for $T \geq T_{\text{cr}}$. An estimate using (23) shows that for most secondary explosives, from $T = T_{\text{cr}}$ at least up to $T = 1000^\circ\text{K}$, in our case ($\tau_d = 10^{-4}$ sec)

$$\begin{aligned}\bar{P}_{\text{ex}} - \bar{P} &< 0.1 \bar{P}_{\text{ex}}, \\ \tau_{\text{ad}} &\leq 10^{-6} (\text{sec}),\end{aligned}$$

in which case, in particular, $\bar{P}_{\text{ex}} - \bar{P}_{\text{cr}} < 0.1 \bar{P}_{\text{ex min}}$. Since the differences $\bar{P}_{\text{ex}} - \bar{P}$ and also $\bar{P}_{\text{ex min}} - \bar{P}_{\text{cr}}$ do not exceed the measurement error, one may consider the analogy between the experimentally obtained behavior of explosives (Figure 13) and the assumed behavior (Figure 4) to be reliable and that we experimentally determine \bar{P}_{cr} for the various explosives (see Table 4). This fact may serve to explain why the measured values of \bar{P}_{ex} , including those of $\bar{P}_{\text{ex min}} \approx \bar{P}_{\text{cr}}$, are independent of the impact velocity.

Strength condition

After having described the experimental results regarding the mechanical properties of explosives, the mechanics of impact with explosive and the average pressures under which fracture (\bar{P}_{mel}) or explosion (\bar{P}_{ex}) of a charge occurs, we turn again to the assumed picture of the "behavior" of explosives in instrument No. 2. For simplicity, we used ideas of the mechanical properties of explosives from the results of ordinary ($h/D \geq 1$) isothermal experiments and the solution of the problem of the isothermal deformation of a thin disk. We were prepared to encounter in the real case arbitrarily major departures from the proposed picture owing to nonisothermicity. That the experiments did not show any noticeable effects of nonisothermicity apart from the initiation of explosion is quite unexpected. Indeed, the solution of the isothermal problem is well satisfied; the charge deformation energy is small and, in addition, it is either semi- or almost entirely elastic. Further, upon impact the charges are brittly fractured, undergoing before destruction a near-elastic deformation.

We now estimate the thermal effect of the deformation, assuming the elastic and inelastic deformations to be of the same order, as is usually the case for brittle polycrystalline bodies, i.e., $\varepsilon = 0.1$ (ε is the relative deformation). Suppose the deformation occurs under a maximum stress equal to the ultimate strength ($\sigma_{\text{ult}} = 350 - 1250 \text{ kg/cm}^2$); the temperature corresponding to such a degree of deformation will be

$$\Delta T = \frac{\sigma_{\text{ult}} \varepsilon}{J_{\text{cp}}} = 1 - 5^\circ\text{C},$$

where $J = 0.427 \text{ kgm/cal}$ is the mechanical equivalent of heat. Since this is an overestimate, we may conclude that ultimate strength is reached in practice isothermally and explosion cannot occur before fracture. On the other hand, we saw above that explosion occurs before the pressure drop, as a result of fracture or explosion. Hence it follows that the formation of

a hot spot and explosion occur during the process of fracture. From this point of view the coincidence of the explosion points with the strength curve (Figure 13) is perfectly natural.

As shown above, in our experiments the induction period $\tau_{ad} \leq 10^{-5}$ sec. What is the fracture time? Fracture and motion of the material begin on the free surface. A pressure drop cannot occur before the fracture wave reaches the charge axis. Hence the fracture time cannot be less than the time of passage of the fracture wave. Since the velocity of the latter does not exceed the velocity of sound (for example, cracks propagate at a velocity which is a factor of 2–3 lower than the velocity of sound), the fracture time under our conditions ($D = 10$ mm) is of the order of magnitude 10^{-5} sec. Thus, the induction period and the fracture time agree in order of magnitude.

It is of interest to estimate the deformation necessary to produce the critical heat-up. The estimate is made in the same way, except that large deformations are usually characterized by the logarithm of the relative deformation (logarithmic deformation). We obtain the following (under-estimate):

$$\ln \varepsilon = \frac{J_{cp} (T_{cr} - T_0)}{\sigma_{ult}} = 10 - 40.$$

Such a large deformation is impossible in brittle materials. Such a deformation puts in mind a liquid rather than a solid. Since we are interested generally in the necessary thermal effect of inelastic deformation, the only such process for solids which is not limited by the magnitude of the deformation up to ultimate strength is friction. These considerations to some extent can serve as a guide when investigating the process of mechanical heat-up.

We have thus shown that initiation in instrument No. 2 occurs upon mechanical failure, if the critical stress condition $\bar{P} > \bar{P}_{cr}$ is satisfied. We turn again to initiating explosives. It is now clear that for them not only the hyperbolic dependence of \bar{P}_{ex} on h/D is satisfied, but also that explosion could not occur before mechanical failure sets in. Thus, the constant C in the experimental dependence (19) is nothing else but ultimate strength σ_{ult} . If we now assume that for initiating explosives the obtained empirical dependence of ultimate strength on temperature, $\sigma_{ult}(\text{kg/cm}^2) = 4.2 T_{mel}(\text{°C})$, is satisfied (as we say, it is satisfied not only for organic compounds), then it can be used for predicting their melting temperatures. Table 6 gives for initiating explosives the ultimate strengths, the corresponding melting temperatures and the ignition temperatures for a 5-second exposure.

TABLE 6. Ultimate strengths, melting and ignition temperatures for initiating explosives

Explosive	σ_{ult} , kg/cm ²	T_{mel} , °C	T_{ign} , °C
Lead azide	1550	(370)	345
TNRS	1220	(290)	265
Tetrazene	750	(180)	154

Such a prediction of the melting temperatures for initiating explosives is probably not very accurate: the empirical dependence itself gives a spread

of $\pm 10\%$. Nevertheless, the obtained melting temperatures do not give rise to immediate objections, since they all lie above the ignition temperatures. In a later discussion on the existence of critical stresses for initiating explosives, they will act as guides for possible melting temperatures of these explosives.

The main problem of this chapter was the investigation of the critical conditions for the initiation of explosion in instrument No. 2, and accordingly we sum up the results of the tensometric measurements. The experiments set up in accordance with the assumed picture of the behavior of the explosives (see Figure 4) clarified fairly well the mechanical aspect of this picture. The initiation of explosion was found to fit the following pattern. A localized hot spot forms, and explosion occurs in the process of mechanical failure of the charge. It was shown that the strength condition

$$\bar{P}_{\text{ult}} = \sigma_{\text{ult}} \left(1 + \frac{D}{3\sqrt{3}h} \right)$$

and the critical stress condition

$$\bar{P} \geq \bar{P}_{\text{cr}}$$

are the critical conditions for the initiation of explosion in instrument No. 2.

The value of the critical stress in instrument No. 2 was found to be independent of the rate of the action. The question of the dependence of \bar{P}_{cr} on h and h/D remained open, and will be clarified in the following chapter when examining the mechanism of localized hot spots. To conclude this chapter we consider the causes of the probabilistic character of fall-hammer tests of explosives, and obtain some additional results with the aid of a definition of the frequency of explosions.

§5. Frequency of explosions

Frequency curves

The most common type of explosive sensitivity test is the fall-hammer test, in which a load falls from a set height, and it is noted whether or not an explosion occurs for the known impact energy. A peculiarity of such tests is that, for various values of the same impact energy, cases with and without explosion occur. A number of tests are therefore performed for each load fall height and the frequency of explosions $f = N_{\text{ex}}/N$ is determined where N_{ex} is the number of explosions and N is the total number of tests (usually $N = 25$). The frequency curve represents the dependence of f on the fall height H_0 (or the impact energy W_0). The treatment of the initiation of explosion as a result of the formation of an effective localized hot spot, due to charge deformation, on the whole does not contain any probability factor. Therefore the probability character of the tests is of special interest.

The probability character of the tests is probably associated with the spread of the quantities determining the initiation of explosion. It is natural to expect that this spread should obey a normal (Gaussian) law of deviation from their average values. Plotted in f , W_0 coordinates, the frequency

curves are asymmetric. In $f, \sqrt{W_0}$ coordinates they acquire symmetry and can be described by a normal probability distribution, implying that initiation of explosion by impact is determined by quantities which are proportional to the square root of the impact energy. There are two such quantities: the pressure developing upon impact and the load velocity at the moment of impact. Tensometric measurements have shown that critical conditions for the initiation of explosion in instrument No. 2 are related to the pressure and are independent of the impact velocity.

Consider now the strength condition which, like the critical stress condition, is a critical condition for initiation of explosion. Since explosion is initiated by mechanical failure, the spread of \bar{P}_{ex} about the average values should be regarded as a spread of the charge strengths. We note that the relative deviation of measured values of \bar{P}_{ult} and \bar{P}_{ex} from their average values are approximately identical for any h (see Figure 15) and attain fairly large values ($\pm 25\%$). Thus, the probabilistic character of the tests is due to the spread of the charge strengths. This, however, raises the question of the causes of this spread, probably due to the irregularity (Kholevo's term) of the prepared charges, which is connected with the pressing of thin layers. Indeed, whereas thin layers, on the one hand, allow high pressures to be attained on weak media, and are therefore necessary for initiating explosion, on the other hand, thin layers make it difficult to press a charge thoroughly and obtain high-quality charges (even under very high pressing pressures the density remains approximately 10% lower than the density of a single crystal). The interdependence of these factors together with the diversity of testing methods yield explosion frequencies below 100%.

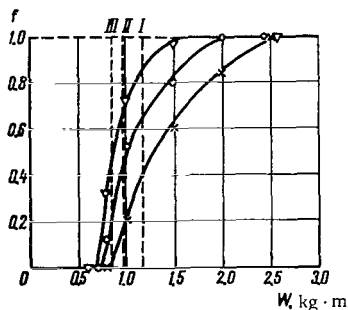


FIGURE 20. Explosion frequency vs. impact energy for oktogen, with various charge thicknesses:

\times — 0.30 mm (I); \circ — 0.35 mm (II); ∇ — 0.40 mm (III).

Using the strength curves (ignoring the spread) and the critical initiation conditions for explosion in instrument No. 2 (the critical stress condition and the strength condition), we construct for this instrument the dependence $f = f(W_0)$, where f assumes the value unity if the critical conditions are satisfied, and zero otherwise. This dependence is termed ideal and will be

compared with the experimental frequency curve. If the impact energy is such that the maximum pressure \bar{P}_m for impact without explosive (see Figure 9) is lower than the critical stress \bar{P}_{cr} , then for any charge thickness there should be no explosion. If the impact energy $W_0 > W_0(\bar{P}_{cr})$, then the following two cases are possible.

First case $h \leq h_{cr}$ (see the pressure oscillogram in Figure 7c). Explosion should always occur when the maximum impact pressure for no explosive, \bar{P}_m , is greater than the pressure required by the strength condition:

$$\bar{P}_m > \bar{P}_{ult} = \sigma_{ult} \left(1 + \frac{D}{3 \sqrt{3} h} \right);$$

then $f = 1$ for $W_0 > W_0(\bar{P}_{cr})$ and $f = 0$ for $W_0 < W_0(\bar{P}_{ult})$.

By using the dependence $\bar{P}_{ex} = \bar{P}_{ex}(h)$ (see Figure 13) and $W_0 = W_0(\bar{P}_m)$ (see Figure 9) for various explosives and any $h \leq h_{cr}$, it is thus possible to find the limit value of the impact energy W_0 for which the ideal function f jumps from 0 to 1. These values are shown in Figure 20 by the vertical dashed lines. The same figure also presents experimental points for the frequency of explosions. The frequency curves are represented by solid curves. The limit values of W_0 , found from tensometric measurements, in practice agree (as follows from the figure) with the 50% ($f = 0.5$) explosion frequency points on the frequency curves.

We make some observations with regard to the width of the (frequency curve) region within which the frequency jumps from zero (W_0^1 —the lower limit of the frequency curve) to unity (W_0^u —the upper limit).

In the ideal case $W_0^1 = W_0^u$ and is equal to the calculated limiting impact energy. In a real case, $W_0^u - W_0^1 > 0$. The relative deviations of measured values of \bar{P}_{ex} and \bar{P}_{ult} from their average values are approximately the same for all h , and therefore the absolute deviations increase as h decreases and \bar{P}_{ex} accordingly increases. This, together with the fact that with increasing maximum pressure \bar{P}_m of impact without explosive $d\bar{P}_m/dW_0$ decreases (see Figure 9), should result in an increase in the width $W_0^u - W_0^1$ of the frequency curves with decreasing h . The frequency curves given in Figure 20 fit this conclusion. The least width of the frequency curve should occur for $h = h_{cr}$.

Second case $h > h_{cr}$ (see the pressure oscillograms in Figure 7b and d).

In this case, as pressure \bar{P}_{ult} determined by the strength condition is attained, the critical stress condition $\bar{P} \geq \bar{P}_{cr}$ is not satisfied, since for $h > h_{cr}$, $\bar{P}_{ult} < \bar{P}_{cr}$ and charge fracture occurs. This results in a decrease in charge thickness to some value h_1 (ejection of part of the charge) and in a decrease in impact energy by an amount ΔW_1 due to seismic and other losses. A lower value \bar{P}_m' of the maximum pressure developed under impact without charge also corresponds to the reduced impact energy $W_0 - \Delta W_1$. Explosion should occur when $h_1 \leq h_{cr}$ and $\bar{P}_m' \geq \bar{P}_{ult}(h_1) \geq \bar{P}_{cr}$, but not when $h_1 \leq h_{cr}$ and $\bar{P}_m' < \bar{P}_{ult}(h_1)$. When $h_1 > h_{cr}$ and $\bar{P}_m' < \bar{P}_{ult}(h)$ there should be neither explosion nor subsequent fracture. When $h_1 > h_{cr}$ and $\bar{P}_m' > \bar{P}_{ult}(h_1)$ a second fracture should occur, resulting in a decrease of charge thickness to some value h_2 and in a decrease of impact energy to $W_0 - \Delta W_1 - \Delta W_2$. Once again explosion should depend on the relationship between h_2 and h_{cr} , as well as \bar{P}_m' , \bar{P}_{cr} , and $\bar{P}_{ult}(h)$.

Whatever the initial charge thickness, explosion can occur only for $h \leq h_{ult}$. The number of sample fractures depends on the impact energy, the initial charge thickness, the total length of the machine rollers, and the total volume of the rollers. The limiting impact energy for which the ideal function f jumps from zero to unity can be found from the following:

$$\bar{P}_m = \bar{P}_m(W_0 - \Delta W_1 - \Delta W_2 - \dots - \Delta W_n) = \bar{P}_{ult}(h_n) \geq \bar{P}_{cr}, \quad (24)$$

where

$$h_{n-1} > h_{cr}.$$

The limit value of W_0 should be determined with the aid of other supplementary dependences. From the large number of pressure oscillograms and the resulting $\bar{P} - \Delta h_i$ diagrams, it follows that the changes in Δh_i and ΔW_i upon each fracture have a considerable spread. Therefore the frequency curves, which are a direct result of the spread, should be very wide in the region $h > h_{cr}$, at least wider than for $h = h_{cr}$. Indeed, the secondary explosives tested with a "standard" charge (50 mg), corresponding to approximately $h = 0.4$ mm of pressed charge (for all the tested secondary explosives, except oktogen, $h_{cr} < 0.4$ mm), give fairly elongated frequency curves. For a number of explosives it is altogether difficult to obtain the fall height for 100% explosions ($f = 1$), due to the anomaly of the frequency curves. Table 7 and Figure 21 present explosion frequency data for some explosives.

TABLE 7. Percentage of explosions for RDX, Tetryl, and TNT in the case of a standard charge (50 mg and $h \approx 0.4$ mm) and for oktogen ($h = 0.5$ mm)

Impact energy, kg · m	Oktogen	RDX	Tetryl	TNT
0.5	0	0	—	—
0.6	0	—	—	—
0.8	12	—	—	—
1.0	48	20	—	0
1.5	68	36	—	—
2.0	—	48	—	—
2.5	96	52 and 68	16 and 0	0
3.0	100	64	4	—
3.5	—	72	16 and 0	—
4.0	100	84	8	—
4.5	—	—	16 and 4	—
5.0	—	80	—	—
5.5	—	—	24	—
6.0	—	92	8	—
6.5	—	—	16	—
10.0	—	—	—	0

The frequency curve for oktogen of charge thickness 0.5 mm is given as an example of a normal pattern of the frequency curve. TNT, Tetryl, and even RDX are anomalous, since by increasing the impact energy we should,

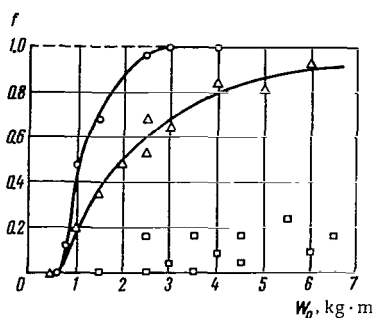


FIGURE 21. Explosion frequency vs. impact energy for Tetryl (□) and RDX (Δ) in the case of a charge thickness of 0.4 mm, and for oktozen (○) in the case of a charge thickness of 0.5 mm.

according to (24), always obtain $f = 1$. Nevertheless, for the beginning of explosion after an impact energy $W_0 = 1.5 \text{ kg} \cdot \text{m}$, Tetryl does not yield any frequency curve with increasing energy, the explosion frequency oscillating between 0 and 0.24 independently of the impact energy. TNT does not explode at all in instrument No. 2 for a standard charge, although the pressure oscillograms show that for high impact energies, for both TNT and Tetryl, pressures considerably exceeding \bar{P}_{cr} are reached after all fractures. An explanation of this anomaly will be proposed in the next chapter.

The behavior of the ideal function $f = f(W_0)$ and the real frequency curves in the two cases $h_0 \leq h_{cr}$ and $h > h_{cr}$ are

in good agreement. The conclusion reached is that the smallest width of the probability region should correspond to $h_0 = h_{cr}$.

Variation of explosion frequency with charge thickness

A major factor for the initiation of explosion in instrument No. 2 is the charge thickness h (the ratio h/D). It is therefore of interest to investigate the dependence $f = f(h)$ for constant impact energy. As above, the critical conditions for the initiation of explosion by impact in instrument No. 2 may be used to construct an ideal dependence $f = f(h) : f = 1$ if the critical conditions are satisfied and $f = 0$ otherwise. Suppose the impact energy is such that the maximum pressure \bar{P}_m for impact without explosive is greater than \bar{P}_{cr} . Then for

$$h < h_1 = \frac{\sigma_{ult} D}{3 \sqrt{3} (\bar{P}_m - \sigma_{ult})}$$

the strength condition is not attained and $f = 0$ (Figure 22). For some $h_2 > h_{cr}$ the function under consideration also vanishes; the larger h , the greater the fracture, thus yielding larger seismic and other losses. The rise in energy losses with increasing h should result in that (24) is not satisfied, and hence $f = 0$. The expected dependence $f = f(h)$ for constant impact energy is presented in Figure 22. (This dependence is simplified in the region $h > h_{cr}$, where it should assume a discrete character.) The experimental explosion frequencies for various charge thicknesses are given for oktozen, RDX, Tetryl, trinitrophenol, and TNT in Table 8 and Figure 23; the impact energy is constant and equal to $2.5 \text{ kg} \cdot \text{m}$.

It follows from above that with decreasing impact energy the region $h_1 < h_{cr} < h_2$, where $f = 1$, should decrease, and in the limit $h_1 \rightarrow h_{cr}$ and

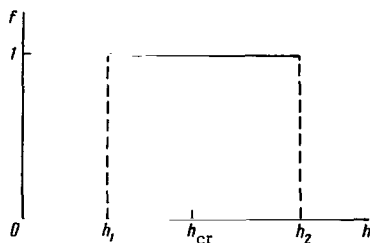


FIGURE 22. Idealized explosion frequency vs. charge thickness for constant impact energy.

$h_2 \rightarrow h_{cr}$ The experimental dependences $f = f(h)$ for various impact energies are shown in Figure 24 (for oktogen). The corresponding data are presented in Table 8.

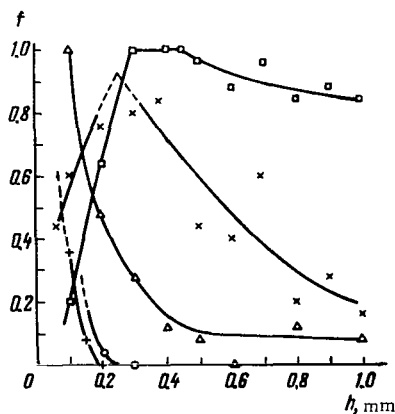


FIGURE 23. Explosion frequency vs. charge thickness for the same impact energy ($2.5 \text{ kg} \cdot \text{m}$) for various explosives:

□ — oktogen; × — RDX; Δ — Tetryl; ○ — trinitrophenol; + — TNT.

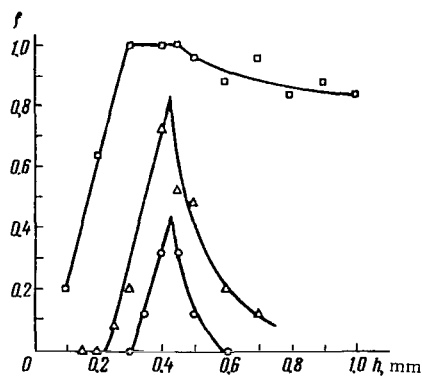


FIGURE 24. Explosion frequency vs. charge thickness in the case of oktogen for various impact energies:

□ — $2.5 \text{ kg} \cdot \text{m}$; Δ — $1.0 \text{ kg} \cdot \text{m}$; ○ — $0.8 \text{ kg} \cdot \text{m}$.

Figures 23 and 24 show that the experiments confirm that maximum frequency occurs for the same values of h_{cr} that were determined above by the tensometric method (Figure 13). In the limit, the minimum energy which is still capable of initiating explosion should be such that the corresponding maximum pressure \bar{P}_m (see Figure 9) equals \bar{P}_{cr} . This limit is characterized by a critical stress \bar{P}_{cr} equal to the pressure as given by the strength condition, i.e., we obtain for h_{cr} the expression*

$$h_{cr} = \frac{D\sigma_{ult}}{3\sqrt{3}(\bar{P}_{cr} - \sigma_{ult})}. \quad (25)$$

* Expression (25) holds if $\bar{P}_{cr} \geq 2.6\sigma_{ult}$.

TABLE 8. Percentage of explosions for various explosives, and different charge thicknesses and impact energies

Explosive	Impact energy, kg · m	Charge thickness, mm														
		0.06	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.70	0.80	0.90	1.00
RDX	2.5	44	60	—	76	—	80	—	84	—	44	40	60	20	28	16
Tetryl	2.5	—	100	—	48	—	28	—	12	—	8	0	—	12	—	8
TNT	2.5	—	36	8	0	—	—	—	—	—	—	—	—	—	—	—
Trinitrophenol	2.5	—	—	—	4	—	0	—	—	—	—	—	—	—	—	—
Oktozen	2.5	—	20	—	64	—	100	—	100	100	96	88	96	84	88	84
	1.0	—	—	0	0	8	20	—	72	52	48	20	12	—	—	—
	0.8	—	—	—	—	—	0	12	32	32	12	0	—	—	—	—
Oktozen (130°C)	1.0	—	—	—	16	—	44	76	40	—	20	—	—	—	—	—

In the ideal case, for all $h > h_{cr}$ and $h < h_{cr}$, $f = 0$, and explosion is initiated only for $h = h_{cr}$.

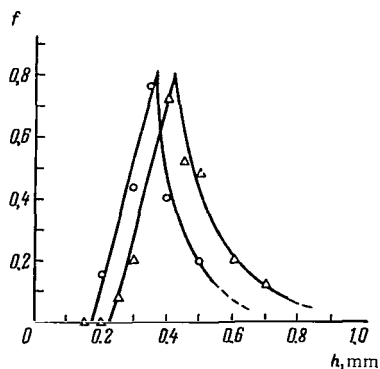


FIGURE 25. Explosion frequency vs. charge thickness for oktozen at various initial temperatures (impact energy $1.0 \text{ kg} \cdot \text{m}$):
 Δ — 20°C ; \circ — 130°C .

Consider now the effect of the initial temperature on the initiation of explosion in instrument No. 2. The maximum explosion frequency was found to occur at the point $h = h_{cr}$ (see Figure 24). As the initial temperature rises, h_{cr} decreases (according to (25)), since the tensile strength decreases with rising temperatures. This should result in the curves $f = f(h)$ being displaced toward smaller h , i.e., the explosion frequency should increase for $h < h_{cr}$ and decrease for $h \geq h_{cr}$. We determined the dependence of explosion frequency on charge thickness for oktozen at normal temperature and at 130°C ($W_0 = 1.0 \text{ kg} \cdot \text{m}$; see Table 8). The results are presented in Figure 25 and completely confirm the above conclusion regarding the influence of the initial temperature. Another confirmation may be the experiments of Vasil'ev /36/, in which a decrease in explosion frequency with increasing temperature was observed for secondary explosives comprising a standard charge (50 mg) in instrument No. 2. Thus, the variation in explosion frequency in instrument No. 2 as the initial temperatures varies is due only to the variation in the ultimate strength of the explosives.

TABLE 9. Charge thicknesses h_{cr} (mm) for transition from fracture to explosion (in instrument No. 2)

Explosive	From pressure measurements	From the frequency peak
Oktogen	0.43	0.42–0.43
RDX	0.25	0.25
Tetryl	~0.12	~0.10–0.13
PETN	0.27	0.27
TNT	~0.08	~0.10

We compare now the results obtained by two independent methods: the determination of the explosion frequency and the measurement of the pressure. Table 9 presents values of h_{cr} corresponding to explosion frequency peaks (see Figures 23 and 24). The discrepancy between the results of the two independent methods does not exceed the error of tensometric measurements. Since the explosion frequency was determined from a larger number of experiments than the pressure measurements, the good agreement between the results of the two methods is an additional confirmation of the critical conditions for the initiation of explosion in instrument No. 2.

Conclusions

Critical hot spot temperatures can be estimated by restricting the induction period of focal thermal explosions to the impact time (10^{-3} sec). For most secondary explosives such temperatures are 400–600°C, much exceeding their melting temperatures. Following the assumption of melting as the limit of localized heat-up, the application of high pressures (of the order of 10^4 kg/cm²) is therefore required for the formation of an effective hot spot. Owing to the low strength of secondary explosives (of the order of 10^2 kg/cm²), under inelastic deformation such pressures can be obtained only in special conditions, the most common example of which are the deformation conditions in thin layers. It is characteristic that all the proposed methods for testing explosives for sensitivity involve deformation in thin layers.

Pressure measurements for impact on a thin layer (instrument No. 2) showed that all the tested explosives (TNT, trinitrophenol, Teteryl, PETN, RDX, oktogen) and inert organic substances after near-elastic deformation undergo mechanical failure, which is accompanied by ejection of some of the material from the region of compression and a sharp pressure drop. The average pressures \bar{P}_{ult} under which sample fracture occurs are well represented by the hyperbolic dependence

$$\bar{P}_{ult} = \sigma_{ult} \left(1 + \frac{D}{3\sqrt{3}h} \right),$$

where σ_{ult} is the ultimate strength, h and D are the height and diameter of the sample.

This dependence is similar to that used in the theory of metal processing of a plastic body by pressure. If \bar{P}_{ult} exceeds some critical value \bar{P}_{cr} (critical stress in instrument No. 2), then an explosion is recorded instead of fracture. The average pressures \bar{P}_{ex} for which explosion is recorded are well represented by the same dependence. An explanation of this is that the formation of localized hot spots and the initiation of explosion take place during the process of mechanical failure of the charge.

The processing of experimental pressure recordings in the study of explosion by the methods of the theory of thermal explosion allowed us to estimate the induction period of self-ignition of a hot spot. The order of

magnitude of the induction period does not exceed 10^{-5} sec (the corresponding critical size of a hot spot is 10^{-4} cm).

With the aid of the obtained critical conditions for the initiation of explosion, namely, the strength condition and the critical stress condition, the observed dependences of the explosion frequency on impact energy, charge thickness, and initial temperature have been explained simply.

Chapter II

MECHANISM OF HEATING EXPLOSIVES TO CRITICAL TEMPERATURES

§1. Nonisometric deformation of plastic bodies

In the previous chapter it was shown that an effective localized hot spot upon initiation of explosion by impact in instrument No. 2 may form only in the process of mechanical failure, if the critical stress condition is satisfied. At the present stage of study it is natural to investigate a wider problem, namely, how a hot spot of temperature equal (or approximately equal) to the melting temperature forms in general upon fracture of a solid. This problem, similar to the general problem of nonisothermal effects upon fracture due to inelastic deformation, was not raised in the literature on strength of materials. Investigation of the fracture of solids (chiefly metals) is carried out experimentally, and usually takes the form of studies into the fracture surfaces under the most foreseeable experimental conditions, most often upon extension (rupture). In such conditions, nonisothermal effects are apparently insignificant, although, as established, fracture cannot be absolutely brittle, because on the fracture surface there are always traces of plastic deformation.

Existing strength theories do not consider the fracture process, but determine only the instant at which it should begin. Such studies do not contribute to our problem. Usually the strength conditions are similar in form to the yield conditions in the theory of plasticity: the latter, however, determines not only how and where they are attained, but mainly considers the course of the plastic deformation under these conditions. Plastic flow and subsequent fracture in solids was investigated by Thomas /77/ by methods of the theory of plasticity (the approach, of course, was isothermal); undamped shear discontinuities (surface of discontinuous rate of straining) were taken for the fracture surface. Experiments set up later confirmed the calculations. We shall proceed to some extent similarly, namely, we look for the interesting nonisothermal effects (not necessarily upon fracture) by examining the behavior of plastic media. This, on the one hand, accords the discussion a general character, while, on the other hand, it allows inclusion of results of a field which is well developed theoretically.

We consider first of all the causes of the localized nature of the hot spot and, in particular, how obligatory is localized heating. Heating should occur when the heat released upon plastic deformation cannot be removed from the deformation zone. The nonuniformity of the deformation throughout the deformed body should result in localized heating. Thus, under conditions of sufficiently rapid deformation, the causes of nonuniform

plastic deformation are those of localized heating. Uniform heating should occur upon uniform deformation. Apart from the trivial and uninteresting case of elastic uniform compression (extension), there are three possible causes of uniform deformation: simple extension, simple compression, and pure shear. We examine in which of these cases the deformation of various plastic bodies is indeed uniform.

The theory of plasticity describes elastoplastic deformations with the aid of two models, namely, a perfectly plastic body and a consolidating body, which cover the plastic properties of real materials. The form of the relationship between the stress σ and strain ϵ for these bodies subject to simple (uniaxial) compression — extension is shown in Figure 26a. When these bodies are loaded, there is elastic deformation at first. When the stress reaches a value $\sigma = \sigma_s$, further deformation of a perfectly plastic body proceeds under a constant stress equal to the yield stress σ_s , and that of a consolidating body proceeds under an increasing stress, owing to the increase in yield stress with strain (the rate of increase of yield stress with strain is $D = d\sigma/d\epsilon$, the modulus of plasticity). The quantity D is a characteristic of the plastic properties of bodies (for consolidating bodies $D > 0$, for perfectly plastic bodies $D = 0$) and can also be used to represent the capacity of various bodies for uniform deformation. (An elastic body may be regarded as the limiting case of a consolidating body for $D = E$.) Transition from uniform to nonuniform deformation is due to instability of the deformation, the modulus of plasticity being an index of the plastic "stability" of the material /78/. Related to the problem of deformation stability is that of the uniqueness of the solution /79/ (in both cases variations of the solution with respect to strain are considered); frequently a nonunique solution is conducive to instability. Bearing this in mind we classify the various bodies with respect to deformation uniformity as a function of the modulus of plasticity (Figure 26a).

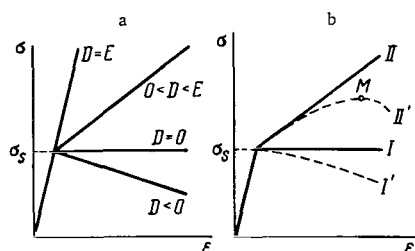


FIGURE 26. Referring to the behavior of plastic bodies under nonisothermal deformation.

(i) $D = E$ — purely elastic medium; the solution is always unique; in all three cases (simple extension, simple compression, pure shear) the deformation is uniform.

(ii) $E > D > 0$ — consolidating medium; all that was said about elastic media remains true, with the exception of the simple extension case; in the case of extension for $D/\sigma \leq 1$ the deformation is unstable, a neck forms and the deformation becomes nonuniform /80/.

(iii) $D = 0$ — perfectly plastic body; in general the solution is not unique, which considerably complicates the theory of perfectly plastic media [81]; in cases of simple extension and pure shear, plastic deformation is unstable and nonuniform; stability and uniformity are preserved only for simple compression.

(iv) $D < 0$ — such a medium, if it exists, should be termed a "weakening" medium; the examples of the above media imply that the smaller D , the less cases remain of uniform deformation; it is clear that a weakening medium is absolutely unstable and its deformation is in all cases nonuniform; for such a medium one should expect the effects of spontaneous development of deformation (for example, upon the application of a "dead" load).

Thus the results of the isothermal theory of plasticity are applied to the nonuniform deformation of bodies characterized by various moduli of plasticity. The above conclusions may be used when considering the possibility of uniform nonisothermal deformation. In this case, one must include the fact that the plastic properties largely depend on temperature: the yield stress decreases with increasing temperature. Whereas under isothermal conditions the rate of straining was unimportant, in the case of nonisothermal deformation this rate is decisive, since the very nonisothermability arises when heat cannot be removed from the deformation zone. Whenever the isothermal deformation was nonuniform, localized hot spots should have formed. The problem of uniform cases under isothermal deformation still remains. It is clear that for uniform deformation, if the heat released upon plastic deformation is not removed (adiabatic conditions), there is a uniform temperature rise throughout the sample and a decrease in the yield stress with strain. Stress — strain relationships for plastic bodies under adiabatic conditions are represented by the dashed curve in Figure 26b. For a body which was perfectly plastic under isothermal deformation (curve I), under adiabatic conditions weakening begins immediately after the elastic part of deformation (curve I'), and for a consolidating body (curve II), weakening starts after some deformation (up to point M) with consolidation (curve II'). With the transition to weakening, deformation should become nonuniform. If the released heat is partially removed, the deformation is also nonuniform due to the appearance of a plastic inhomogeneity in the medium itself (at different points of the body the yield stress varies due to the nonuniform temperature distribution).

Thus, nonisothermal deformation of a body which is perfectly plastic under isothermal conditions is always nonuniform. As regards nonisothermal deformation of a body which was consolidating under isothermal conditions, uniform deformation can be realized upon adiabatic deformation only up to point M (see Figure 26b); after point M, the deformation is always nonuniform. Since we are interested in hot spots close to the melting temperature, near which the yield stress tends to zero, it is clear that in such a case point M should be passed. Thus, it can be concluded that plastic deformation resulting in the required hot spot is always nonuniform and, consequently, heating upon deformation of plastic bodies can only be localized.

Continuing the discussion of nonisothermal deformation of plastic bodies, we note that the established localized character of the hot spot does not yet yield concrete information on the heating mechanism and says nothing, in particular, about the size of the hot spot zone. The character of the deformation localization may apparently vary with the geometric, dynamic and

kinematic conditions of deformation [75, 76]. Analysis of these problems, however, encounters extreme difficulties as a result of the undeveloped state of the theory of nonisothermal deformations. Being content with a qualitative approach, we consider a particular case of nonisothermal deformation of plastic bodies, namely, deformation under shear (see Figure 27).

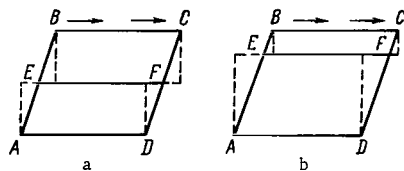


FIGURE 27. Illustration for the discussion of the heating mechanism of a medium under shear.

We turn first to a perfectly plastic body. Since only an adiabatic relation (Figure 26, curve I') follows directly from the isothermal dependence of stress on strain (Figure 26, curve I), we consider in the first place the possibility of an adiabatic case of deformation under shear — a case when the rate of straining and the size of the deformation zone are such that heat transfer may be neglected. To begin the discussion we assume that the process is adiabatic. Then, a perfectly plastic body in the adiabatic case (Figure 26, curve I') deforms elastically up to $\tau_s = \sigma_s / \sqrt{3}$, and then plastically with a negative modulus of plasticity, i.e., like a weakening medium. Within the elastic range the deformation is uniform and there is no heat release. Maximum elastic shear (the stress is then equal to the shear strength τ_s) is shown in Figure 27 by solid lines (ABCD). Further increase in shear deformation should bring the sample into a plastic state. Plastic deformation, however, will be unstable and nonuniform, since any increase in shear, say in the region near the surface EF, causes localized weakening (a decrease in shear strength), in view of which all subsequent plastic deformation is concentrated in this region.

Under progressive decrease in shear strength in the region of plastic deformation, the remaining part of the sample (outside this region) cannot be under a large stress and spontaneous elastic unloading should occur there. The potential energy stored in the sample under elastic deformation is then realized in the work of plastic deformation localized in the region about EF. To illustrate plastic instability of deformation (region EF may form and develop in any section of the sample) Figure 27 is given in two versions (a and b). Turning now to the region of plastic deformation (a region situated "near" some surface EF) and applying to it the previous arguments with regard to deformation instability, we should finally derive that the whole plastic deformation is concentrated along the surface EF (as shown in Figure 27). Then surface EF is a discontinuity for the rate of straining and a plane source of heat release.

A plane source of heat release cannot exist under adiabatic conditions. Although the discontinuity in rate of straining takes place physically not

along a surface, but along a layer of finite thickness, where large shear deformations occur, the heat release process apparently cannot proceed adiabatically, since this layer is assumed to possess extremely small thickness /78/. Thus, we have a contradiction: assuming the deformation to be adiabatic, we found a deformation nonuniformity whose scale is incompatible with the requirement of an adiabatic state. Suppose now the requirement of an adiabatic state is removed and we allow for heat transfer. Despite a number of complications, the general features of the process should be preserved. Thus, the temperature should be a maximum (and consequently, the yield stress a minimum) in the place where the source is operating; self-localization of the deformation in some plane EF with transformation of elastic energy of the sample into plastic deformation work at the discontinuity should also take place. However, weakening due to the effect of heat transfer should be less intense, and the corresponding stress-strain curve should be situated between curves I and I' (see Figure 26b).

Thus, heat transfer "dampens" the process. An important feature of the process is its spontaneity, in that after reaching the yield stress it subsequently can develop independently without the action of external forces; in this case the elastic energy source in the sample serves as the energy source for heating. The hot spot temperature should be determined by the dependence of the yield stress on temperature, on the amount of stored elastic energy, and on the heat transfer.

Consider now a medium which is consolidating under isothermal deformation conditions (see Figure 26, curve II). An adiabatic stress-strain dependence is shown in Figure 26b by the dashed curve (curve II'). Under sufficiently rapid shear the deformation will be close to adiabatic, and then uniform up to point M ($D > 0$). After point M ($D < 0$) the process just discussed should develop. Thus, this process is common for all plastic bodies. For such a process to take place, there should be no tensile stresses perpendicular to EF, so that a rupture does not form at the discontinuity; compression, on the other hand, prevents the formation of ruptures /82/. Deformation conditions at the discontinuity can be considered analogous to friction: friction of plastic bodies and plastic deformation on slip planes should be regarded as a single friction-gliding process /83/.

Thus, the qualitative analysis of deformation of plastic bodies under shear gives rise to the concept of a new, essentially nonisothermal type of process resulting from the instability of the deformation, and brings about a discontinuity in the rate of straining. The process is due to the decrease in yield stress with increasing temperature and develops spontaneously upon transformation of elastic energy into plastic deformation work. A quantitative description of the process (even under the simplest idealization) encounters the difficulties of investigating a complicated nonlinear equation.

Since a new process is being dealt with it is worthwhile referring to another process where similar phenomena are observed, namely, the formation and development of necks when testing plastic metals under tension. A neck forms at any part of a stretched sample when the deformation stability is upset. Further plastic deformation is concentrated in the neck. In this case one also observes spontaneous transformation of elastic energy stored in the sample into plastic deformation work of the neck. This effect is stronger the longer the stretched sample /84/, and for a sufficiently long sample the process should be quite spontaneous, i.e., formation of a

neck and rupture of the sample should take place without increasing the overall deformation of the sample (without additional work by the external forces) /85/. Localization of plastic deformation, both under nonisothermal shear and in the neck upon stretching, is caused by localized lowering of the necessary deformation force; however, in the case of nonisothermal shear the cause of this lowering is the decrease in yield stress with increasing temperature, and in the case of stretching it is the decrease in sample cross section. Deformation in the neck is often accompanied by noticeable heating, which is limited, however, by the magnitude of the neck deformation before rupture.

The discussion of idealized models of plastic bodies allowing infinite plastic deformation is very valuable, even though the properties of these models are far from those of solid explosives. Nevertheless, as a result of this discussion it was possible to approach, though qualitatively, the little-studied problems of nonisothermal deformation and discover a new mechanism of localized heating. These ideas will be applied to the mechanical failure of a brittle body under shear.

§2. Description of the heating mechanism

If (see Figure 27) the ultimate strength τ_{ult} is reached under shear, a fracture surface (for example, the plane EF) forms. Under further shear (due to heat release on this plane upon friction and local temperature rise) the ultimate strength decreases and becomes smaller than that in the remainder of the sample. The remaining parts of the sample should be elastically unloaded to a lower stress equal to the ultimate strength on the plane EF, since the sample cannot exist under different stresses (upsetting of the equilibrium forces). The elastic energy thereupon released should transform into friction work on the same plane (resulting in a larger decrease in strength), elastic unloading of the remaining part of the sample is required, etc. This process is continuous and develops spontaneously. The elastic energy then transforms into friction work until the melting temperature is reached and the liquid phase forms, after which the elastic energy transforms into deformation work of the viscous layer. The process terminates when all the elastic energy of the sample is consumed, as well as that part of it which transformed into kinetic energy of the relative motion of the upper and lower parts of the sample. Since the kinetic energy also should transform into deformation work of the melted layer, when calculating the energy balance, one may not therefore consider it separately and assume that the total amount of heat released upon various forms of inelastic deformation (friction, flow of viscous liquid) is simply equal to the elastic energy stored by the sample upon shear. We make some remarks as to the role of uniform compression in the process in question. The elastic energy of uniform compression does not contribute to the heating. However, the presence of uniform compression is important, since (a) it hinders the formation of a crack, (b) the specific friction force is equal to τ_{ult} if the normal stress exceeds σ_{ult} , and (c) the melting temperature depends on the uniform compression pressure.

The above process satisfactorily meets the requirement of this heating mechanism of solid explosives. Furthermore, the process takes place

after ultimate strength has been attained, and is related to friction and deformation of the liquid, as pointed out in Chapter I, §4 regarding the possibility of producing a specified hot spot temperature by inelastic deformation. A rigorous quantitative approach to such a process is even more difficult than in the case of plastic bodies, due to the new factor of melting. In addition the following inconsistency arises: according to the viscous liquid model the shearing stress is proportional to the viscosity coefficient and the velocity gradient, i.e., near the thin layer this stress is known to be greater than the ultimate strength of the solid phase, which is independent of velocity and vanishes near the melting temperature. This implies that the solid state is more easily fractured than the liquid is sheared, and it is not clear how the liquid could form. Without entering into the details of this inconsistency, the process occurs at the junction of the viscous liquid and solid models; near the interface the solid phase is probably "lost" in the liquid. (This idea can perhaps, to some degree, be used to understand the concept of a lubrication boundary, but the appearance of all the other factors is complicated by a phase transition.) Then the overheating of the liquid phase relative to the melting temperature should be fairly small, since the heat released upon viscous deformation is spent on melting the dispersed (solid) phase, distributed in the liquid. Whereas heat transfer to the solid phase (both dispersed and bordering on the zone of viscous or viscoplastic deformation) should take place by heat conduction, heat transfer in a fast-deforming liquid apparently takes place by convection, which contributes to temperature equalization in the deformation zone. These considerations with regard to the causes hindering overheating of the liquid phase relative to the melting temperature can be regarded (allowing for the highly complicated nature of the process) only as assumptions of interest in connection with the assumption of melting temperature as the heating limit. As regards the possibility of liquid formation in the analyzed process, the attainability of the melting temperature follows from experiments on friction of metals /28/, and the possibility of melting upon friction follows from the well-known process of metal welding by friction /86, 87/. We note that by using the analogy between welding of metals and friction, we bypass the physical complications of the analyzed process by reference to a known fact.

Wherever a fracture surface EF (see Figure 27a and b) appears under shear, the heating resulting from the considered spontaneous process should be the same. If we assume a rectangular heating profile, then its size r will be determined by the melting temperature and the elastic energy stored in the sample, which depends on the sample volume Sa . Equating the elastic energy of sample shear to the amount of released heat, we have

$$\frac{\tau_{ult}^2}{2G} Sa = Jr\rho S [c(T_{mel} - T_0) + L], \quad (26)$$

where G is the shear modulus of the explosive; L is the heat of fusion; S is the cross-sectional area of the sample (we assume the cross-sectional dimensions of the sample to be much larger than its height a). Expression (26) yields

$$r = \frac{\tau_{\text{ult}}^2 a}{2JG\rho [c(T_{\text{mel}} - T_0) + L]}, \quad (27)$$

where the melting temperature depends on the pressure.

Approximating the temperature distribution by a rectangular profile may be justified for r exceeding the characteristic dimension of the heating, i.e., for $r > \sqrt{\chi\tau}$ (χ being the thermal diffusivity of the explosive and τ the time of the spontaneous process). If $r < \sqrt{\chi\tau}$, then the process, starting as friction at the fracture surface, cannot attain the melting temperature due to heat transfer. To determine τ , a quantitative theory of the process is required. However, it can be affirmed that with increasing pressure of the uniform compression and with increasing melting temperature for a sample of finite dimension a , it is always possible to transfer the nonisothermal process to the solid phase.

In the shear scheme under consideration the fracture surface EF could form anywhere in the sample (see Figures 27a and b). Under more complicated deformation conditions (complicated state of stress) the formation of a fracture surface and the subsequent nonisothermal spontaneous process can occur only where discontinuity of the rate of straining is assumed, since the geometric and kinematic deformation compatibility conditions must be satisfied.

§3. Experimental confirmation of the heating mechanism

Experiments with model charges

Upon deformation in instrument No. 2, a discontinuous rate of straining is postulated over the major part of the contact surfaces, where the shearing strength is reached. At the same time, a discontinuity cannot form at the central plane of the sample ($z = 0$), where the shearing stress vanishes (see Figure 3a). To check this conclusion we set up experiments with model charges in conjunction with M. Yu. Kosygin.

The model charges consisted of a secondary explosive (oktogen) with a thin layer of lead azide sprinkled either on the central plane, or on the upper and lower planes (contact planes) of the charge. The behavior of charges with a layer of lead at the center did not in any way differ from the behavior of oktogen itself. When the layer of lead azide was situated on the contact planes (upper, lower, or simultaneously on both), a detonation always occurred for the same charge thicknesses, whereas pure oktogen would only fracture ($h > h_{\text{cr}}$). Before describing other experiments which confirm the proposed mechanism, we consider two results obtained using layered charges. One is the determination of the critical stress \bar{P}_{cr} for lead azide in instrument No. 2, and the second is the experimental demonstration of the independence of \bar{P}_{cr} on h and h/D . From experiments with oktogen (Figure 28) it followed that a thin layer of lead azide does not alter the strength of the charge (the strength corresponded to that of oktogen). At the same time, a layer of lead azide deposited on the contact planes contributes to the initiation of explosion. Bearing this in mind experiments were set up to determine \bar{P}_{cr} of lead azide. The existence of a critical

stress in lead azide is indicated by the predicted melting temperature (370°C), and this is lower than the melting temperature of the admixtures (500°C) which Bowden [19] found to have a sensitizing effect. At the same time, the critical stress \bar{P}_{cr} in instrument No. 2, if it exists, should be lower than 3700 atm, since under this pressure lead azide placed at the contact of the charge with the roller always led to the explosion of 1.0-mm-thick charges based on oktogen. To determine \bar{P}_{cr} of lead azide we therefore used secondary explosives (TNT, Tetryl, PETN, and RDX) as a strength basis, since they are weaker than oktogen. The measured pressures in experiments with layered charges are given in Figures 28 and 29. The horizontal dashed lines in Figure 28 mark the region of spread of the measurement results upon transition from fracture to explosion. No points are given inside the region, and the points outside the region correspond to the average values of \bar{P}_{ult} and \bar{P}_{ex} for many measurements. The points in Figure 29 (the strength basis is TNT) correspond to the results of individual measurements, including the transition region. The solid horizontal line in Figure 28 is the selected value of \bar{P}_{cr} for lead azide. For different strength bases it remains at the same value of 2600 (± 200) atm. Thus, over the investigated range of charge thicknesses \bar{P}_{cr} is independent of h and h/D , since as h varies h/D varies too. The dependence of \bar{P}_{cr} on h and h/D remained the last question which required clarification in connection with the assumed behavior of explosives (see Figure 4).

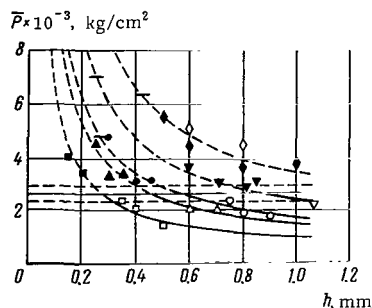


FIGURE 28. Average pressures upon fracture (open shapes) and upon explosion (filled shapes) vs. charge thicknesses of secondary explosives sprinkled with a layer of lead azide:

◆ — oktogen; ▽ — RDX; ● — PETN;
 ▲ — tetryl; □ — TNT (◊ — oktogen charges with lead azide at the central plane).

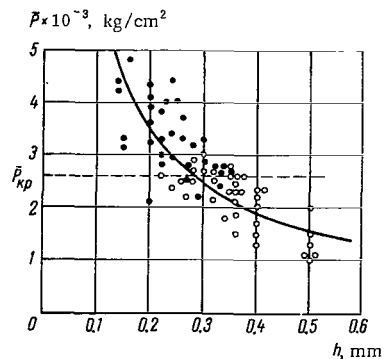


FIGURE 29. Spread of the measurement results in the transition region from fracture to explosion for TNT charges sprinkled with a layer of lead azide.

Behavior of explosives under static compression

Charges of oktojen, RDX, PETN, Tetryl, and TNT were slowly loaded in instrument No. 2. A 30-ton press was used for loading. Charges of various thickness were tested. The residual variation of the charge thickness with pressure was measured. The data for TNT are given in Figure 30. Fairly thick charges ($h_0 > 0.8$ mm) are fractured under the same pressures (within the usual spread) as under impact (the strength curve obtained for TNT under fall-hammer impact is represented in Figure 30 by the dashed curve). Charges of lower thickness are not always fractured upon loading and may be continuously deformed up to such high pressures as 20,000 atm. Above this pressure measurements were not performed, since at approximately 20,000 atm residual deformation of the rollers sets in and their contact surfaces become concave. Until the pressure corresponds to the strength curve obtained under impact, the deformation of the charge increases slowly with pressure, and then the residual deformation increases more rapidly with increasing pressure, i.e., considerable plastic deformation occurs, which however is accompanied by consolidation, whence the static loading curve lies above, and is steeper than, the strength curve.

Thus, under static loading and not too large h_0 TNT behaves as a consolidating body and allows considerable plastic deformation. Mechanical failure often occurs on the static loading curve, and is more frequent the thicker the sample and the more rapidly the load is applied (loading was manual, and therefore there is no point in introducing specific loading rates). The behavior of the remaining tested explosives is similar to that of TNT, the transition to plastic deformation being correlated with its impact strength curve.

Two factors bring about this behavior of explosives under static compression and, in particular, its departure from the behavior under impact, namely, the influence of the rate of loading, which in the cases being

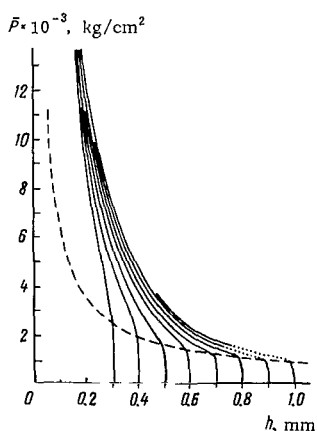


FIGURE 30. Static loading curves for TNT charges of various thicknesses (under a press).

compared differs by 3–4 orders, and the influence of the pressure. As is known, the possibility of relaxation processes depends on the rate of loading, and when this is increased, it usually causes transition to brittleness. However, the influence of the rate alone is insufficient, since samples with a large ratio h/D behave brittly both under impact and under static loading, including tests of pressed charges ($h/D \geq 1$) upon crushing. A considerable influence on the mechanical properties of solids is exerted by the pressure /89/: in particular, it increases the plastic deformation of metals before fracture, and marble, brittle under ordinary conditions, becomes a plastic material under high pressure. If, however, a material is deformed plastically under pressure and then the pressure is removed, brittleness is restored.

The considerable influence of the pressure in our case follows from the following experiment. Samples were deformed under static loading to some thickness h_i , which differs appreciably from the initial thickness h_0 , and a pressure much exceeding $\bar{P}_{ult}(h_i)$ was applied. The samples were then subjected to an impact. The ultimate strength of the samples corresponding to the strength curve was then obtained. In this way plastic consolidation of samples is removed as the pressure is decreased.

Let us summarize the above. For large h/D , when the pressure is low, explosives behave brittly both under impact and under static compression; for small h/D and higher pressure, under static-loading conditions, they acquire the capacity to deform plastically, and under conditions of impact loading (high loading rate) they behave brittly.

Fractures often occur on the static loading curve for higher pressures, the smaller h_0/D . Mechanical failure may also occur upon removal of the load [88]. It is important in this connection that sample fracture is replaced by explosion for the same values of \bar{P}_{cr} which were obtained under impact. However, upon fracture, due to the increase in pressure with decreasing h/D a pressure of \bar{P}_{cr} or of some value close to it is only obtainable for some optimum initial charge thickness h_0 (for TNT this value is approximately 0.4 mm, which corresponds to a charge of 50 mg). The values of \bar{P}_{cr} found in static loading experiments amount for TNT to 10,500, for RDX to 6700, and for oktogen to 6100 atm. (For Teteryl, a maximum fracture pressure of 6000 atm and a single explosion at 9000 atm was obtained; it was not possible to cause explosion of PETN under static loading, fractures occurred only for large h_0/D and pressures not higher than ~ 3000 atm; in the experiments it was apparently not possible to find the optimum charge thickness h_0 for these explosives.) The agreement between the \bar{P}_{cr} values obtained under impact and static loading is perfectly clear from the viewpoint of the proposed hot spot mechanism, since the rate of the spontaneous process should not depend on the rate of the external action.

Frequency curve anomaly

For some explosives there is a frequency curve anomaly in the region $h_0 > h_{cr}$, in that the explosion frequency does not attain 100% however large the impact energy (see Table 7; Figure 21). The proposed hot spot mechanism makes it possible to explain this anomaly on the basis of the finite amount of elastic energy stored in the sample which, for some limiting charge thickness h_{lim} , may be insufficient to create a spot of the required temperature and size. Suppose h_{lim} is not much smaller than h_{cr} ; then the charge thickness, decreasing during fractures and material ejections, may turn out to be below h_{lim} , in which case no explosion should occur. However large the impact energy, the explosion frequency no longer depends on the impact energy but is determined by the number of cases when the charge thickness, decreasing in jumps, enters the interval h_{cr} to h_{lim} .

There are two reasons why it is difficult to accurately estimate h_{lim} . First, this quantity should refer to a spot of minimum size, the ignition of which results in a self-propagating explosive transformation. If, following Bowden, we assume this size to be 10^{-5} cm, then, for RDX, expression (27)

yields a value of a_{lim} equal to 0.3 mm. Second, the use of expression (27), which was obtained for "free" shear, is hardly possible for the deformation conditions in instrument No. 2, where, upon the transformation of the elastic shear energy of any element into deformation work at a discontinuity, the elastic energy itself of this element can be replenished by additional shear due to the large radial pressure gradient (see Figure 3b), so resulting in an overestimated value of h_{lim} by expression (27). We note that the final thickness of the charges which failed in the tests is equal to several hundredths of a millimeter; the value of h_{lim} for the tested explosives is apparently close to 0.1 mm.

Comparison of the tested explosives with respect to the extent to which an anomaly appears, fits in well with this explanation. An anomaly should be more strongly pronounced, the smaller the interval $(h_{cr} - h_{lim})$. Indeed, an anomaly is absent in the frequency curve of oktogen (see Figure 21) for which $h_{cr} = 0.43$ mm, it is appreciable for RDX ($h_{cr} = 0.25$ mm), it is very pronounced in the case of Tetryl ($h_{cr} = 0.12$ mm) and it is extremely pronounced for TNT ($h_{cr} \approx 0.08$ mm), which on the whole does not explode with a "standard" charge in instrument No. 2.

Only instrument No. 2 has been considered, since all the experiments were performed in this instrument. In each case only the charge thickness was indicated, since the diameter remained constant ($D = 10$ mm). When there is reason to believe that \bar{P}_{cr} does not depend on h and h/D , one can transform (in accordance with the assumed behavior of explosives (see Figure 4)) to h/D in place of h and speak, for example, of $(h/D)_{cr}$ instead of h_{cr} , which till now referred only to instrument No. 2. If the diameter D is reduced, then h_{cr} should also decrease in a way so that $(h/D)_{cr} = \text{const}$. Hence it follows that with decreasing D (and consequently also h_{cr}), an anomaly in the explosion frequency should become more and more evident until h_{cr} becomes smaller than h_{lim} , after which there should be no more explosions at all.

In this connection consider Weller's fall-hammer experiments ($D = 1.5$ mm) and introduce the following notation (allowing for the different diameters) for the charge thickness corresponding to transition from fracture to explosion: h_{cr}^w for the Weller tests and h_{cr}^{II} for tests in instrument No. 2. From $(h/D)_{cr} = \text{const}$ it follows that $h_{cr}^w = 0.15 h_{cr}^{II}$, i.e., for secondary explosives (at least for most of them) $h_{cr}^w < h_{lim}$, which accounts for the absence of explosions in the Weller tests. Instances of the disintegration of secondary explosives under the high impact energies of a Weller fall hammer are apparently due to the heating up of soft-metal elements upon their deformation; however, this still requires additional verification. The situation with initiating explosives, for which $(h/D)_{cr}$ is large, is different. For example, in the case of lead azide

$$(h/D)_{cr} = \frac{\sigma_{ten}}{3 \sqrt{3} (\bar{P}_{cr} - \sigma_{ten})} = 0.43, \quad (28)$$

whence $h_{cr}^w = 0.64$ mm. To detonate initiating explosives by a Weller fall hammer, fairly low impact energies are necessary as a result of the smaller striker area.

§4. Examination of known models of the medium and of heating mechanisms

The above experimental results were obtained in instrument No. 2. The mechanical properties of solid explosives, the deformation regime and the critical initiation conditions under these conditions were studied, and ideas on the mechanism of heating up to critical temperatures were also developed. The resulting experimental data were used to examine a model of a medium corresponding to solid explosives and the heating mechanism, which in the absence of these data assumes a hypothetical character. The analysis at this stage of the discussion should also serve as an additional verification of the heating mechanism proposed in the present work.

We turn first of all to the inhomogeneity of the system, accorded great importance by many investigators. The possibility of a localized hot spot forming due to inelastic deformation at inhomogeneities (plastic deformation of individual grains, their fracture and friction with one another) was pointed out by Khariton /13/, and later by Kistiakovski and Connor /7/. Later, Kholevo /2, 3/ (comparing the behavior of regular explosives in instrument Nos. 1, 2, and 3) and Sukhikh and Khariton /27/ (observing the fracture of brittle charges upon impact along glide planes) found that inelastic deformation of the charge as a whole is decisive in the initiation of explosion. This result, which serves to correlate the experimental results, formed the basis of the present work, and no exceptions have been observed.

Now we attempt to explain why inhomogeneities do not influence the initiation of excitation, and find those cases for which the influence of inhomogeneities may be considerable. The inhomogeneity of a system can be characterized by the size of the explosive particles and by the size of the cavities around which numerous local fractures occur during loading. The fracture fragments and the cavities are apparently close in size. For local fracture to result in explosion, the pressure should not be less than the actual critical stress \bar{P}_{cr} and the size a of the fracture zone not less than a_{lim} , the scale of the inhomogeneity essential for the initiation of explosion:

$$\begin{aligned} \bar{P} &\geq \bar{P}_{cr}, \\ a &\geq a_{lim} = \frac{2JEpr_{cr}}{\sigma_{ult}^2} [c(T_{cr} - T_0) + L] \sim \frac{1}{\sigma_{ult}^2}. \end{aligned} \quad (29)$$

This relation was obtained from /27/. In the proportional relation a quantity which varies strongly for different explosives was isolated. Use was made of

$$\tau_{ult} = \frac{\sigma_{ult}}{\sqrt{3}} \text{ and } G = \frac{E}{2(1+\mu)} \quad (30)$$

where the Poisson coefficient μ is taken as 0.5. As long as the pressure is lower than \bar{P}_{cr} , any inhomogeneities should be ineffective. At high pressures, only those inhomogeneities of size greater than a_{lim} can lead to explosion. It is important that with increasing pressure, the system inhomogeneity decreases strongly in comparison with the initial situation: for example, subject to pressing, the grains are crushed and the cavities between them

decrease correspondingly. Hence in the case of secondary explosives, for which \bar{P}_{cr} is of the order of 10^4 atm and a_{lim} is apparently larger than 0.1 mm, inhomogeneities are ineffective whereas charge deformation as a whole is decisive for explosion initiation. This is also true for mixtures of secondary explosives, which are also unaffected by inhomogeneities /90/. It follows from (29) that inhomogeneities should show up if \bar{P}_{cr} and a_{lim} are small, in other words, if \bar{P}_{cr} is small and σ_{ult} is large. The role of inhomogeneities therefore may prove important in the case of (at least some) initiating explosives of large grain size, since when tested in finely dispersed form the influence of inhomogeneities was not noticed (see Figure 18).

Sukhikh and Khariton /27/ noted that traces of melting were observed on glide planes at which charges fractured, and that the melting temperature was indicated as the limit of heating. This fits in well with the conclusion of the present work, that melting occurs upon mechanical failure at surfaces of discontinuous rates of straining.

Kholevo /2, 3/ accorded great importance to deformation at inhomogeneities from the point of view not only of the initiation mechanism, but also of the deformation mechanism. This, however, does not contradict his conclusion as to the necessity of charge deformation as a whole for the initiation of explosion. Thus, Kholevo assumed that, at the initial stage of impact, the explosive crystals deform plastically and melt at the boundaries, thereby forming a structured system which then behaves like a Bingham body. To characterize the mechanical properties of explosives, which show up upon impact loading, Kholevo made wide use of the term "fluidity," understood as the ability of the charge to be squeezed out upon impact from beneath the punches. The "charge fluidity" was assumed to depend on the yield point and the melting temperature of the explosive. Hot spots in the flow of a heterogeneous structured system should have a localized character, and after reaching the melting temperature are regarded as viscous spots.

Since the rate of heat release upon deformation of a viscous liquid is proportional to the coefficient of viscosity and the square of the velocity gradient, Kholevo considers that the maximum rate of heat release under definite deformation conditions may occur for some optimum charge fluidity, since the rate of heat release is low for low viscosity, and for high viscosity the velocity gradients are small. Explosion is initiated when the rate of heat release is sufficient to create high-temperature hot spots whose ignition time is shorter than the remaining time of impact. Hence the rate of straining and the impact time along with the charge fluidity and the reaction capability of the explosive are considered as the basic factors which determine explosion initiation. Methods of measuring fluidity were not proposed and the question whether the explosive fluidity is high or low was decided by comparing the frequency of explosions in instruments Nos. 1 and 2. Kholevo's proposed model of deformation and initiation by impact explained qualitatively the influence of the deformation conditions on the test results. By now much work /6, 8, 37, 61, 91, 92, etc./ illustrating Kholevo's idea has been carried out. Neither Kholevo's nor any subsequent work confirms that crystalline explosives deform under impact as a viscoplastic body. The results of the present work contradict the "viscoplastic body" approach to solid explosives. This even refers to such systems as an explosive with a paraffin-type admixture /64, 93/, which appear to be closest to Kholevo's model. Since the idealization of the mechanical properties of any specific model depends on the rate of straining and the

corresponding temperature, it may be assumed that the viscoplastic model is realistic in the case of impact deformation for solid explosives with a very low melting temperature, or for initial temperatures close to the melting temperature. In this connection we note that the above-mentioned puzzling behavior of dina ($T_0/T_{\text{mel}} = 91$) may be due to its proximity to the viscoplastic case of deformation, since the annealing of the rollers upon explosion of dina has, in contrast to the other tested solid explosives, the same channel-like form as upon explosion of ballistites in the zone of viscoplastic deformation.

Rideal and Robertson /23/ first considered the problem of focal thermal explosion and estimated the critical temperatures of the hot spots for secondary explosives. Since these temperatures were found to be considerably higher than the melting temperatures, the authors proposed the following heating mechanism: when impact-testing secondary explosives some liquid phase forms, which, due to the pressure drop, undergoes in the sample a high-rate capillary flow and in viscous flow heats up to critical temperatures. The evaluation of these temperatures in capillary flow (using the Hagen - Poiseuille law) completely satisfied the authors of the work. However, V. S. Kozlov reported that it was found impossible to initiate explosion of TNT and trinitrophenol heated to 130°C by pressing through a capillary even under stricter conditions than in the calculations of Rideal and Robertson.

Only those results of the investigations of Bowden et al. /11, 19/ which refer to solid explosives will be considered. The principal result refers to the melting temperature as the limit of mechanical heating (the influence of the pressure on the melting temperature was ignored), on which to some extent the other results are based. In Bowden's opinion, of all solid explosives only the initiating ones can explode due to heat release under proper deformation, since they spontaneously ignite when heated before the onset of melting. In this connection it is assumed that localized hot spots form upon the friction of crystals with one another and with the surface of the acting body. If we assume the above-mentioned melting temperatures of initiating explosives and the critical temperatures determined by Bowden in experiments with admixtures, then the melting temperatures of both initiating and secondary explosives are lower than the critical temperature. Then a corresponding critical stress should exist and the friction mechanism of the crystals should be ineffective. Indeed, the existence of a critical stress was shown above for lead azide and, in addition, the inhomogeneity of the system was not observed to affect the initiation of these explosives (we recall that initiating explosives were used in a finely dispersed form). According to Bowden, explosives for which $T_{\text{ult}} < T_{\text{cr}}$ cannot be exploded due to self-heat-up upon deformation, and the only two mechanisms that may be responsible for initiation of explosion are heating due to adiabatic compression of gaseous inclusions and heating of high-melting ($T_{\text{mel}} \geq T_{\text{cr}}$) admixtures by their friction with one another and with the surface of the striker. The sensitizing effect of such admixtures was shown by Bowden in many experiments (in the case of low admixture concentration one can hardly speak of their friction with one another).

Consider now the mechanism of adiabatic compression of gaseous inclusions. It is known that if rapid compression of the gas takes place independently of the deformation of the explosive (compression of the gas by a piston above a layer of explosive), then (for a 20-fold compression of

the air) the explosive can be easily ignited /19, 94/. At the same time, if gaseous inclusions less than 0.1 mm in size are present in the explosive, the compression upon impact should be almost isothermal /20/. The inefficiency of the adiabatic compression mechanism of gaseous inclusions for standard explosives follows from Kholevo's experiments in instrument No. 3 with poured charges. Comparing the behavior of PETN situated on an anvil in the form of a ring (a large gaseous inclusion) and in the form of a continuous layer, Bowden obtained a larger percentage of explosions for the former and regarded this as confirmation of his viewpoint. However, it was sufficient to increase the height of the ring and of the disk in order to reverse the picture (the experiments of Andreev et al.), although the air compression factor should in this case increase. We note that in Bowden's experiments with PETN pressures above 12,000 atm develop upon impact; the results of these experiments correspond well to data obtained in the present work for pressed PETN charges, when initiation due to adiabatic compression of gaseous inclusions is clearly impossible. Initiation of solid explosives by impact was not related by anyone to the mechanism of gaseous inclusions. The inefficiency of the latter mechanism for solid explosives may be explained as follows: already under fairly low pressures the grains begin to break down, the greater part of the air escapes from the charge (the above-mentioned partial scattering of a poured charge is probably due to air seepage through the pores), the brittleness of the explosive prevents "sealing" of gaseous inclusions, the remaining air scatters throughout the charge, and the size of the inclusions becomes so small that they are compressed isothermally.

Bowden carried out tests under rapid shear according to a scheme close to that shown in Figure 1e, but he did not obtain explosions for secondary explosives. He therefore concluded that these explosives cannot be exploded as a result of heating by inelastic deformation and, in particular, by friction, since the melting temperatures (the heating limit) of secondary explosives are lower than their flash point. Later, on the basis of the increase in melting point with pressure, Kozlov used the same scheme to carry out tests under higher compression pressures and obtained the explosion of all the materials he tested. Kozlov assumes that localized hot spots result from heat release due to external (dry) friction at the interface of the explosive with the body acting on it. (Testing by a scheme (see Figure 1e) following Bowden is called friction testing.) Kozlov interpreted his experimental results (which appear to lead directly to an understanding of the role of pressure in the initiation of explosion by mechanical action) as a refutation of the assumption of the melting temperature as the limit of heating, although under high pressures they constituted such a refutation only as regards the normal melting temperature. According to the mechanism proposed in the present work, friction at a surface of discontinuous rate of straining is one of the principal stages of the heating process; the discontinuity surfaces, depending on the deformation conditions, may be situated inside the charge and yet coincide with the contact surfaces (for deformation in thin layers the latter case prevails). If the pressures are sufficiently high (appreciably above \bar{P}_{cr}), explosion should occur due to heating only by dry friction until the process becomes one of melting (a condition for this is that the rate of heat release upon chemical reaction exceeds the rate of mechanical heat release).

Bolkhovitinov /29, 31, 37, 38/ undertook a quantitative approach to initiation processes. He used the model of a viscous liquid to describe the behavior of solid explosives under impact /37, 38/, and the model of a perfectly plastic body to formulate the critical deformation conditions /31/. Despite the fact that in both cases one determines the rate of heat release under inelastic deformation, the deformation conditions themselves were assumed isothermal in the sense that allowance was not made for the variation of the mechanical constants (coefficient of viscosity, yield point) with temperature. This remark also refers to /39/, where use was also made of the model of a perfectly plastic body and, although the case in question was of developed plastic deformation, attention was not given to the possibility of a variation in deformation conditions under impact due to heat release. Bolkhovitinov generalized the assumption of melting as the limit of heating /29, 31/, which led to an understanding of the role of pressure upon initiation by mechanical action and opened wide possibilities for a quantitative study of the phenomenon.

The principal viewpoints in the literature on the mechanism of deformation and initiation were examined, as well as the experimental explosion-frequency results obtained by various investigators in different instruments. We attempt to explain them on the basis of the concepts developed in the present work.

§5. Applicability of our results to general deformation conditions

The experimental results described above were obtained with instrument No. 2 and the critical initiation conditions were investigated under the corresponding conditions. For a constant critical stress in instrument No. 2, these results should be applicable to deformation conditions similar to those of instrument No. 2, i.e., for different diameters.

The behavior of explosives in Weller's tests ($D = 1.5$ mm) was interpreted above, and the results may also help in understanding the experimental results of Andreev and Terebilina /6/ in instrument No. 4 proposed by them (see Figure 31a). Two types of experiment were performed, namely, when the explosive charge is placed at the center of the rollers (charge diameter 5 mm) and when the charge is uniformly distributed over the end plane of the rollers ($D = 19$ mm); in addition, the charge weight was varied (2, 10, 50 mg). The results are presented in Table 10 (K-44-2 fall hammer, 10 kg load, fall height of load 25 cm). When the charge is located centrally, a large percentage of explosions is observed for those explosives with large $(h/D)_{cr}$ (for example, initiating explosives and secondary explosives, like PETN, RDX, and oktozen). If $(h/D)_{cr}$ is small (TNT, trinitrophenol), a large percentage of explosions is observed for a uniformly distributed charge. The influence of the charge weight on the explosion frequency is interpreted similarly.

Andreev and Belyaev /36/ give results obtained under different deformation conditions. Consider now the results of V. S. Oreshin's experiments, which were carried out according to the scheme shown in Figure 31b. Initially the explosive charge is subjected to a high pressure (see the variation of instrument No. 1). Then the connecting sleeve is brought by impact (or manually through a lever) into a position corresponding to instrument No. 2 (in Figure 31b it is shown by the dashed line). The explosive charge is

TABLE 10. Percentage of explosions in instrument No. 4 initiated by fall-hammer impact

Explosive	$T_{\text{mel}}, ^\circ\text{C}$	$T_{\text{fl}}, ^\circ\text{C}$ (according to Kast)	$T_{\text{fl}}, ^\circ\text{C}$ (5 sec)	Weight, mg					
				centrally located			uniformly distributed		
				2	10	50	2	10	50
Trinitrobenzene	122.5	no explosion	550	4	8	4	20	56	4
TNT	80.5	300	475	0	0	0	4	24	4
Trinitrophenol	121.9	300	322	12	32	36	0	64	24
Trinitroresorcinol	178	225	—	32	32	84	4	0	8
Trinitroxylene	182	330	—	8	20	44	4	12	36
Trinitroaniline	191.5	225	—	0	4	12	0	0	0
Trinitrodiaminobenzene	289	—	—	4	32	4	0	0	0
Tetryl	131	190	257	16	20	16	8	0	44
Hexyl	240	250	325	96	100	92	8	8	8
RDX	201	220	260	96	92	92	0	0	0
Oktogen	280	—	335	92	100	—	0	0	4
PETN	141	210	225	64	92	84	0	0	8
Dina	52	235	—	16	44	60	4	68	88
Hexanitrodiphenyl	240	>320	—	28	68	44	0	0	28
Hexanitrodiphenyl oxide	260	—	—	92	100	60	84	68	20
Hexanitrooxanilide	331	>330	—	76	100	100	0	4	8
Lithium picrate	—	—	—	20	12	16	0	0	12
Lead picrate	—	285	—	—	100	—	—	88	—
Potassium picrate	—	—	—	68	100	96	0	0	8
Potassium styphnate (disubstituted)	—	—	—	4	100	100	0	0	0
Ammonium azide	—	—	—	8	64	0	0	4	4
Lead azide	—	330	345	100	—	—	—	8*	—
Potassium azide	—	—	—	100	—	—	—	12*	—
Mercury fulminate	—	170	210	100	100	100	60	92	96
TNRS	—	—	265	100	100	100	0	56	12
Tetrazene	—	140	154	100	100	—	20	64	96
Ammonium perchlorate	—	310	—	48	84	84	—	4	0

* 20 mg sample.

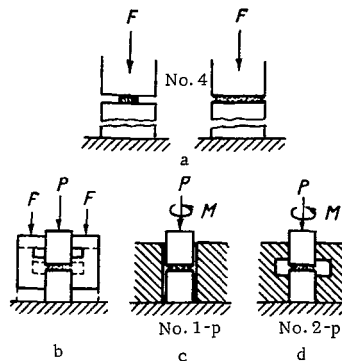


FIGURE 31. Some explosive test schemes.

separated from the sleeve by a rubber ring, which prevents friction between the sleeve and the charge during its movement. In the experiments the frequency of explosions was determined as a function of the applied pressure. A value of 50% explosions was obtained for PETN at a pressure of 4700 atm, which agrees with the critical stress in instrument No. 2 (see Table 4; Figure 13). The results of these experiments are of interest from the point of view that explosion is initiated in this case by spontaneous deformation of the charge under the effect of the elastic energy stored upon compression.

Consider now tests of explosives under rapid shear. V. S. Kozlov and V. A. Mamaev /17/ carried out tests by the scheme shown in Figure 1e. They determined the explosion frequency as a function of pressures \bar{P}_{fric} (50%) and \bar{P}_{fric} (100%), the pressures for which the explosion frequency is respectively 0.5 (50%) and 1 (100%). The table also presents values of $\bar{P}_{\text{fric M}}$ (100%), obtained by S. M. Muratov using the same setup, but with the explosive charge placed in a tin ring.

A similar scheme was used by V. M. Bochkov and V. A. Kupriyanov. They produced shear in instruments Nos. 1 and 2 by rotating the roller through 10° (30 mg charge).

TABLE 11. Critical stresses (in thousands of kg/cm²) obtained in different instruments

Explosive	\bar{P}_{cr}	\bar{P}_{fric} (50%)	$\bar{P}_{\text{II-p}}$ (50%)	\bar{P}_{fric} (100%)	$\bar{P}_{\text{II-p}}$ (100%)	$\bar{P}_{\text{fric M}}$ (100%)	$\bar{P}_{\text{I-p}}$ (30%)	$\bar{P}_{\text{I-p}}$ (100%)
TNT	~11	7.2	6.8	11	9.6	10.8	9.6	—
Trinitrophenol	~9.5	5.7	—	7.4	—	—	—	—
Tetryl	~8.4	4.7	—	6.1	—	6.8	—	—
RDX	7.0	4.2	5.2	5.7	7.2	6.8	6.5	9.6
PETN	4.8	3.1	2.8	5.4	4.8	5.3	5.3	8.7
Lead azide	2.6	1.6	—	3.1	—	1.8	—	—

Table 11 gives the following values of the specific pressing pressures $\bar{P}_{\text{I-p}}$ (30%) and $\bar{P}_{\text{I-p}}$ (100%) for instrument No. 1, and $\bar{P}_{\text{II-p}}$ (50%) and $\bar{P}_{\text{II-p}}$ (100%) for instrument No. 2. In addition, the table gives the critical stresses

\bar{P}_{cr} in instrument No. 2 obtained by us upon impact. The identical trend of all the tabulated pressures is noteworthy. This trend is illustrated by the graphs of \bar{P}_{fric} (50%) and \bar{P}_{II-p} (50%) versus \bar{P}_{cr} (Figure 32), P_{I-p} (100%) versus \bar{P}_{cr} (Figure 32), as well as \bar{P}_{fric} (100%), $\bar{P}_{fric M}$ (100%), \bar{P}_{II-p} (100%) and \bar{P}_{I-p} (30%) versus P_{cr} (Figure 33).

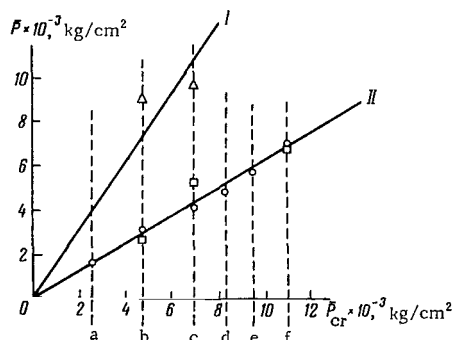


FIGURE 32. Comparison of results obtained by impact and by rapid shear or friction.

The abscissa axis gives the critical stress \bar{P}_{cr} in instrument No. 2, and the ordinate axis gives: I - \bar{P}_{I-p} (100%) (Δ); II - \bar{P}_{fric} (50%) (\circ) and P_{II-p} (50%) (\square). a - lead azide; b - PETN; c - RDX; d - Tetryl; e - trinitrophenol; f - TNT.

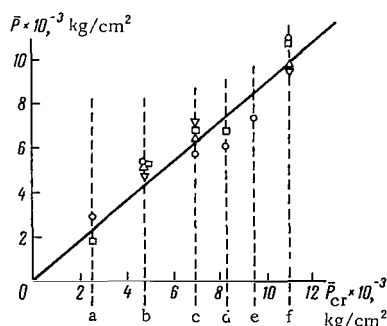


FIGURE 33. Comparison of results obtained by impact and by rapid shear or friction.

The abscissa axis gives the critical stress \bar{P}_{cr} in instrument No. 2. The ordinate axis represents the following: \circ - \bar{P}_{fric} (100%); \square - $\bar{P}_{fric M}$ (100%); ∇ - \bar{P}_{II-p} (100%); Δ - \bar{P}_{I-p} (30%). a - lead azide; b - PETN; c - RDX; d - Tetryl; e - trinitrophenol; f - TNT.

In the schemes shown in Figures 1e and 31d shear occurs "in instrument No. 2," and in Figure 31c shear occurs "in instrument No. 1." The values of \bar{P}_{cr} are approximately equal to the compression pressures, to which correspond 100% explosions upon shear "in instrument No. 2." At the same time they considerably exceed the pressures corresponding to 50% explosions upon shear "in instrument No. 2," and are approximately a factor of 1.5-2 lower than the pressures \bar{P}_{I-p} (100%) corresponding to 100% explosions upon shear "in instrument No. 1." We recall that from an estimate made in Chapter I, §2, the true critical stresses P_{cr} were a factor of 2-2.5 greater than \bar{P}_{fric} (100%).

To explain the difference in the absolute values of the critical stresses referring to different conditions (instrument No. 2 - impact; instrument No. 2 - shear; instrument No. 1 - shear), we turn to the distribution of the hydrostatic pressure in instrument No. 2 (see Figure 3b, the dashed line). We will use this distribution, although it is apparently well satisfied only near mechanical failure. The \bar{P}_{fric} values in Table 11 were obtained for a 2 mm displacement of the upper roller. However, Mamaev showed that the results are only slightly modified if this displacement is only 0.1 mm. Hence it follows that explosion occurs at the beginning of the displacement, and therefore one can use the initial distribution of the hydrostatic pressure. Mamaev placed a crystal of PETN at points of various radii on a tin disk, and showed that the lowest compression pressures required to initiate explosion correspond to a central position of the crystal. Hence it follows

that initiation of explosion upon shear in scheme e (see Figure 1) occurs under a maximum pressure which is approximately a factor of 2–2.5 as high as the average pressure, i.e., higher by a factor equal to the amount by which the expected values of \bar{P}_{cr} exceed $\bar{P}_{fric}(100\%)$. For shear in instrument No. 2 caused by rotation of the roller, initiation of explosion should also occur near the center, since a displacement of 0.1 mm is already attained 1 mm from the center. Similarly agreement between \bar{P}_{II-p} and \bar{P}_{fric} for the same explosion frequency (see Figures 32 and 33) is quite clear. As regards shear "in instrument No. 1," the pressure distribution for a very small gap should be uniform /95/.

In reality, the distribution uniformity is apparently distorted, since in the case of uniformity the tests should not have a probabilistic character. The pressure distribution will be taken as approximately uniform, i.e., $\bar{P} \approx p$ (for 100% explosions the distribution is apparently closest to uniform). When the distribution is uniform, the transition to explosion would be connected with the attainment of the true critical stress \bar{P}_{cr} . Some indication of this is the fact that the values of $\bar{P}_{I-p}(100\%)$ exceed the values of $\bar{P}_{fric}(100\%)$ and $\bar{P}_{II-p}(100\%)$ by approximately a factor of 1.5–2. Such a relationship between P_{cr} and \bar{P}_{cr} , namely, $P_{cr} \approx 1.5-2 \bar{P}_{cr}$, follows from Figure 32, the proportionality factor being rather closer to 2. The correlation of the critical stresses in the various instruments is confirmed by the fact that each of the values (including the critical stress \bar{P}_{cr} in instrument No. 2, obtained by impact) is determined mainly by the true critical stress.

Although agreement between the results obtained in the cases of impact and shear is in general fairly good, analysis of finer effects is difficult owing to the lack of exact data on the stress distribution and a quantitative theory of the heating mechanism.

We shall digress and make a comment on initiating explosives and related melting temperatures. Table 12 presents values predicted above for their melting temperatures T_{mel} , $\bar{P}_{fric}(50\%)$, $\bar{P}_{fric}(100\%)$, and \bar{P}_{cr} (in thousands of kg/cm²), as well as for the flash point T_{fl} for a 5-second exposure, and for the melting temperature $T_{mel adm}$ of the admixtures which in Bowden's experiments /19/ had a sensitizing effect. The existence of critical stresses indicates that the melting temperature is below the critical temperature. The predicted melting temperatures are indeed lower than the melting temperatures $T_{mel adm}$ of admixtures sensitizing the explosive (we recall that $T_{mel adm}$ was interpreted by Bowden as the critical temperature of the hot spots). Thus, though the predicted melting temperatures for initiating explosives are not very accurate, they nowhere contradict known data.

TABLE 12. Some characteristics of initiating explosives

Explosive	$T_{fl}, ^\circ C$	$T_{mel}, ^\circ C$	$T_{mel adm}, ^\circ C$	$\bar{P}_{cr} \cdot 10^{-3},$ kg/cm ²	$\bar{P}_{fric}(50\%) \times$ $\times 10^{-3},$ kg/cm ²	$\bar{P}_{fric}(100\%) \times$ $\times 10^{-3},$ kg/cm ²
Mercury fulminate	210	—	510	—	0.5	0.8–0.9
Lead azide	345	(370)	500	2.6	1.6	3.1
TNRS	265	(290)	480	—	1.0	1.9
Tetrazene	154	(180)	390	—	0.8–0.9	1.5

Consider further the initiation of explosion by impact in instrument No. 1 (see Figure 1a). The explosion frequency in this instrument largely depends on the size of the gap. Corresponding to this case is the problem of forging in the theory of metal processing by pressure (for example, forging of sleeves). This problem cannot be solved rigorously and simplifications are usually introduced, for example, two mean deformation pressures, forging in the gap (setting a strip of thickness l and width h) and setting the main disk (with a ratio h/D) are combined.

In a similar manner the average fracture pressure in instrument No. 1 is

$$\bar{P}_{\text{ult}}^I = \sigma_{\text{ult}} \left(1 + \frac{h}{2\sqrt{3}l} + \frac{D}{3\sqrt{3}h} \right), \quad (31)$$

where l is the size of the gap.

Using expression (31), we consider qualitatively the initiation of explosion by impact in instrument No. 1. The critical stresses in instrument Nos. 1 and 2 are assumed to differ only slightly upon impact, i.e., $\bar{P}_{\text{cr}}^I \approx \bar{P}_{\text{cr}}$. Then, in view of the rise of the strength curve, according to (31), the charge thickness h_{cr}^I at which transition from fracture to explosion should occur in instrument No. 1 should be larger than the charge thickness for instrument No. 2 ($h_{\text{cr}}^{\text{II}}$), and the larger the difference the smaller the gap. As a result TNT, whose $h_{\text{cr}}^{\text{II}}$ or $(h/D)_{\text{cr}}^{\text{II}}$ is small, explodes in instrument No. 1 with a "standard" charge, whereas it did not explode in instrument No. 2, and the explosion frequency of Tetryl increases as compared with instrument No. 2. Since $h_{\text{cr}}^I > h_{\text{cr}}^{\text{II}}$, such a substance as RDX ($h_{\text{cr}}^{\text{II}} = 0.25$ mm), when tested in instrument No. 1, is situated for a "standard" charge in the region $h < h_{\text{cr}}^I$. This even follows from the fact that its explosion frequency increases with increasing temperature (Table 13) (the increase in explosion frequency is connected in this case with the decrease in tensile strength of the material). For high-melting explosives in instrument No. 1, one often observes 0% explosions for a "standard" impact energy ($W_0 = 2.5$ kgm), which in accordance with expression (31) is due to their high strength (the strength condition breaks down). An increase in h_{cr}^I (as a function of gap size) as compared with $h_{\text{cr}}^{\text{II}}$ should result in the disappearance of the frequency curve anomaly, since the interval between h_{cr}^I and h_{lim} increases. In fact, Tetryl ("standard" charge) in instrument No. 1 yields frequency curves, which with increasing impact energy attain 100%. The complexity of instrument No. 1 as compared with instrument No. 2 consists in that the behavior of explosives in the former instrument is determined by two dimensions (h and l , $D = \text{const}$), whereas in the latter instrument it is determined only by one (h , $D = \text{const}$).

In P. I. Vasil'ev's experiments /36/ the variables were the gap size, and the initial temperature T_0 on which σ_{ult} depends. When comparing the influence of the gap and of the temperature, the results obtained by Vasil'ev (see Table 13) can be well accounted for by means of the strength condition in instrument No. 1 (see equation (31)) and the critical stress condition $\bar{P} \geq \bar{P}_{\text{cr}}^I$. One can also account for the influence of preliminary pressing of the charge, which, depending on the gap size, can for various explosives both increase and decrease the explosion frequency. This explanation is based on the increase in plasticity of the explosives under increased pressures subject to static loading (this phenomenon was discussed above) and consists in the

following: when prepressed, the explosive may be partially extruded into the gap so altering the strength condition (31). If this extrusion is fairly small, we have approximately

$$\bar{P}_{\text{ult}}^1 = \sigma_{\text{ult}} \left(1 + \frac{h + \delta}{2\sqrt{3}l} + \frac{D}{3\sqrt{3}h} \right),$$

where δ is the height to which the gap is filled.

TABLE 13. Percentage of explosions in instrument No. 1 as dependent on the gap size

Explosive	$T_{\text{mel}}, ^\circ\text{C}$	Prepressing pressure, kg/cm ²	$T_0, ^\circ\text{C}$	w_0 , kgm	Gap size, μ			
					0-20	21-40	41-60	61-80
Trinitrobenzene	122.5	0	20	5	68	60	20	—
		3840	20		32	33	10	0
		3840	118		100	22	0	0
Tetryl	131	0	20	2	0	50	10	0
		3840	20		0	0	50	10
		3840	125		14	23	10	0
Xylyl	182	0	20	4	0	20	40	0
		3840	20		0	0	10	10
		3840	173		23	25	13	0
RDX	201	0	20	2	30	80	100	—
		1920	20		5	22	31	100
		1920	195		82	100	100	100
Trinitromesitylene	238	0	20	5	27	50	40	20
		1920	20		12	12	44	70
		1920	210		82	100	100	100

Thus, the influence of prepressing shows up by modifying the strength condition. We mention experiments for determining the explosion frequency in instrument No. 1 by impact, where the gap is partially filled with an inert substance (the experiments were performed with Tetryl and wax was used to fill the gap /92/). Since the gap between the sleeve and the lower roller was filled up, the factor 1/2 in the second term of formula (31) should be omitted. The analysis of the initiation of explosion in instrument No. 1 as a function of various factors is to a certain extent qualitative (the formulas used are approximate, the annularity of the gap may be deformed due to displacement of the rollers). Even more complicated for analysis is what is known as a "standard" instrument (see Figure 1d). An additional complication as compared with instrument No. 1 is caused by the use of rollers with bevels. Although many regularities obtained for instrument Nos. 1 and 2 may also appear in the "standard" instrument, it seems to us that it too is unsuitable for research purposes and for explosive sensitivity tests.

An attempt was made in /30/ to confirm the role of pressure in the initiation of explosion by impact (the critical stress condition in the terminology of the present work). For this purpose use was made of Leitman's data /33/, obtained in instrument No. 1, and a comparison was made between the pressures \bar{P}_m developing upon impact, corresponding to 50% explosions, and the difference between the 5-second exposure flash point and the melting

temperature (implying that this difference is at least correlated to the difference between the critical and melting temperatures). Although this

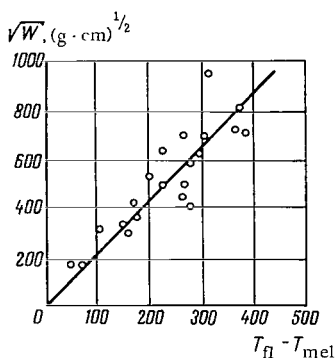


FIGURE 34. The difference $(T_f - T_{mel})$ vs. maximum impact pressure $/30/$.

comparison yielded the proportionality $\bar{P}_m \sim T_f - T_{mel}$ (Figure 34), this result (despite the correctly expected $P_{cr} \sim T_{cr} - T_{mel}$) should be regarded as accidental, since the condition $\bar{P}_{ult} = P_{cr}$ is satisfied only for $h = h_{cr}^I$, and the latter was hardly correct for all the 21 substances used in the comparison.

To conclude this discussion of the behavior of explosives under various deformation conditions, we note that the results of testing explosives in different instruments are not only well interpreted by means of the ideas developed above for the conditions of instrument No. 2, but also present additional confirmation. A result obtained earlier may hence be generalized: the problem of initiation of explosion by mechanical action generally reduces to a mechanical (isothermal) problem with a specially imposed condition on the

uniform compression pressure $P \geq P_{cr}$. (In this case, however, one has the restriction that the size of the deformed charge should not be smaller than some limiting value, determined by the elastic energy reserve necessary to create an effective hot spot.)

Conclusions

Analysis of nonisothermal deformation of plastic media shows that, upon plastic deformation, hot spots approaching the melting temperature can only be attained locally. The specific heating mechanism then depends on the deformation conditions. Here, the heating mechanism upon shear was treated. It was found that nonisothermal shear of plastic bodies should cause a discontinuity in the rate of straining, resulting in heat release. The elastic energy stored in the sample then transforms into deformation work at the discontinuity, constituting the energy source of the heating. An important feature of this process is its spontaneity. Localized heating upon shear is due to the instability of nonisothermal deformation.

Introducing various physical complications the heating process upon plastic shear was applied to brittle fracture, which, as shown in Chapter I, causes the initiation of solid explosives by impact. Friction and subsequent melting at the surface of discontinuous straining rate during mechanical failure are analogous to the phenomena occurring upon friction welding of metals. A number of results confirmed the proposed heating mechanism. Thus, experiments with model charges have shown that the formation of hot spots and the initiation of explosion in instrument No. 2 takes place at the contact surfaces where the rate of straining becomes discontinuous upon fracture. Confirmation is also provided by experiments on the initiation of explosion by slow compression, which indicates the spontaneity of the

process. From the proposed mechanism follows the concept of a limiting (least) sample size, for which the elastic energy reserve is sufficient for the formation of an effective hot spot. This concept enables one to explain the determining role of the deformation of the charge as a whole in the initiation of explosion by mechanical action. The anomalous pattern of the frequency curve, mentioned in Chapter I, was also explained.

Study of the heating mechanism yielded the following important result: the problem of explosion initiation by mechanical action generally reduces to a strength (isothermal) problem with an additional condition for the uniform compression pressure (the applicability of the problem is restricted to some limiting charge size). This conclusion allowed the numerous experimental results obtained for the initiation of explosion under various deformation conditions to be interpreted.

Chapter III

A QUANTITATIVE APPROACH TO THE SENSITIVITY OF SOLID EXPLOSIVES TO MECHANICAL ACTION

§1. The growth of explosion during mechanical action

The existence of a definite sensitivity to mechanical action involves a contradiction (see §1 of the Introduction). The initiation conditions alone (the critical stress condition and the strength condition) do not yield such a characteristic, but only determine the formation of a self-igniting hot spot; nothing is predicted after localized self-ignition. At the same time it is known (for example, from fall-hammer tests) that an explosive transformation, starting locally, may subsequently damp out. Belyaev, Bobolev, and Ratner /97/ proposed that the probability of explosion by impact be regarded as the product of the probability that a hot spot be created and the probability that an explosive transformation propagates from the spot. It is clear that when studying the sensitivity of explosives to mechanical action, the propagation of the explosive transformation must be studied as well as the initiation process. Until now the initiation of explosion, i.e., the formation of a critical-temperature hot spot and self-ignition, has been discussed. The propagation of the explosive transformation from the initial hot spot has been studied far less. A specific feature of the propagation under the action of an impact, for example, is that the propagation occurs in a thin layer of explosive subjected to high pressure. The question of the minimum size of the hot spot whose ignition results in a self-propagating process remained open. Bowden et al./11, 19, 22/, Bobolev and Dubovik /66, 98, 99/ investigated the conditions for self-propagation using high-speed photography. In these experiments the anvil or one of the bodies containing the charge were made of a transparent material (glass, Plexiglas).

In Bowden's impact experiments with liquid explosives the hot spot was confined by the fairly small cavity in the striker. In this case burning, the speed of which rapidly increases to approximately 300—400 m/sec, develops first, to be followed by a sudden transition into a low detonation speed (detonation occurs ahead of the accelerating flame front). A similar picture is obtained for initiation by a spark and an exploding wire in a thin layer of liquid explosive bounded by solid surfaces. If initiation is created by exploding a crystal of lead azide, then low-speed detonation may occur at once. The majority of experiments with liquid explosives were carried out with nitroglycerine.

In the case of solid explosives, we discuss first the growth of explosion in a thin layer (1 mm), initially pressed by a pressure of approximately 1000 atm, and for initiation by heating or by an exploding wire /98/ (Figure 35).

The propagation of the explosive transformation from the hot spot is an initial acceleration followed by a constant speed. The following explanation of such

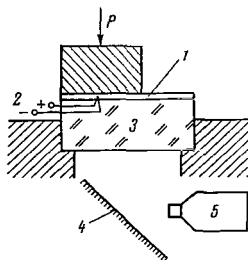


FIGURE 35. Experimental layout for investigating the growth of explosion in a thin layer under pressure (initiation by heating or exploding wire):

1—layer of explosive; 2—wire; 3—transparent base; 4—mirror; 5—photorecorder.

a process and, in particular, of its self-acceleration seems to us appropriate. As the flame propagates from the hot spot, the removal of gaseous reaction products is practically eliminated. Hence a high pressure develops in the products and they play the role of a piston, acting radially on the surrounding explosive and creating a disturbance in the form of compression waves. The movement of material ahead of the flame front destroys the continuity by producing fractures, into which hot gases penetrate and intensify fracture formation. The burning assumes a jet character (in high-speed photography one can see numerous sharp luminous ejections, which branch away from the main region surrounded by glow). An increase in burning surface and in the pressure in the products contributes to the progressive burning-up of the material and to the intensification of the compression waves, which in principle may cause the transition of burning to detonation, unless the jet burning conditions are stabilized.

For not too strong explosives the propagation accelerates smoothly and, attaining 300 m/sec for Tetryl and 500 m/sec for dina, continues at a constant velocity (in this case there are apparently stabilized jet burning conditions). For powerful explosives, the flame accelerates to 300–500 m/sec after which a sharp transition occurs to steady-state propagation conditions with velocities of 700 m/sec for oktogen, 700–800 m/sec for RDX and 900–1000 m/sec for PETN. These conditions have a wave origin, since they arise ahead of the accelerating flame front. In view of the orders of magnitude of the velocities it is natural to assume low-velocity detonation conditions. A direct confirmation of the proposed interpretation of the conditions may be derived from the following experiment /66/. An obstacle (a brass plate 1 mm thick set in Plexiglas) is placed in the path of a steady-state process. For oktogen, RDX and PETN transmission occurs through the obstacle and continues at the same velocity, while for Tetryl and dina there is no transmission. In powerful explosives like PETN, a low-velocity detonation is unstable, after which it gradually accelerates to 1100 m/sec and jumps to a normal-velocity detonation. Acceleration and transition to detonation are apparently the result of wave intensification of explosive burning behind the low-velocity detonation front, unless this burning is prevented by large deformation of the shell. If a compressed explosive develops into a noncompressed one, then it is of interest to know the changes which occur upon the propagation of explosion from the compression region into the noncompressed explosive. In the above experiments it was found that low-velocity detonation then becomes normal-velocity detonation, corresponding to the bulk density, and rapid combustion (up to 500 m/sec) is damped.

Some experimental results regarding the growth of explosion by impact on a thin explosive layer (0.1 mm) are given /19/. Whereas for PETN rapid burning was accelerated in the compression zone to approximately 1000 m/sec

and upon emergence into noncompressed material transferred sharply into low-velocity detonation (from 1000 to 2500 m/sec, depending on the density and thickness of the explosive layer), for RDX and Tetryl the burning is accelerated to lower velocities (100–300 m/sec) and is damped upon emerging from the compression zone. In cases of impact and the creation of a hot spot by a fairly small amount of lead azide in RDX and Tetryl, low-velocity detonation develops at once, and is transmitted to the explosive surrounding the striker, slightly increasing the velocity. The picture of the growth of explosion in such a thin layer of PETN, which is densely pressed between solid surfaces (in the case of initiation by a wire), is similar to that obtained by impact. Mercury fulminate and organic azides behave similarly to PETN. When inorganic azides are placed as a thin layer between solid surfaces and initiated by a spark or a hot wire, they detonate with low velocities of between 770 m/sec (calcium azide) and 2300 m/sec (lead azide). At the same time (as already mentioned) charges of azide and mercury fulminate ($h \geq 0.2$ mm) detonate by impact in instrument No. 2 with a normal velocity, a fact attested to by the fracture of the rollers.

All the described data on explosion propagation, despite their disconnectedness, give some qualitative idea about the character of the processes taking place and indicate their complicated dependence on experimental conditions (layer thickness, pressure, etc.). At present there is no quantitative theory of the observed conditions, propagation limits and transition of various conditions into others. Since the propagation conditions of an explosive transformation may differ, for practical estimates of the sensitivity of explosives one must determine not only whether this transformation will propagate, and if it will in what form, but also the initiation conditions of the explosive transformation.

§2. Classification of mechanical action

The sensitivity of an explosive to some action implies its ability to react to this action upon the initiation of burning, explosion or detonation [36]. Sensitivity to a shock wave implies the initiation of detonation, and sensitivity to thermal action implies the initiation of ignition. From this point of view the concept of sensitivity to mechanical action is essentially undefined. When we discuss the sensitivity of an explosive to mechanical action, we must state which explosive transformation is under consideration. This problem should be investigated by studying practical sensitivity problems within the framework of the theory of explosives. A particular problem is the reliable mechanical initiation of a definite regime of explosive transformations. Here the formulation is clear. Another problem is the evaluation of the danger in handling and producing explosives. In a number of cases the danger for some specific state of an explosive transformation is also clear. Bearing in mind the conditions for the propagation of an explosion, we introduce a classification of mechanical actions, dividing them into two categories:

A. Deformation in a confined space (pressed charges, pencil charges, ammunition, explosive shells). Under these conditions localized ignition is sufficient for the explosion to propagate throughout the space, i.e.,

the determining factor is the initiation process, and the hazard should be evaluated on the basis of the following processes: action (deformation); hot-spot formation in the explosive; thermal self-ignition. To each particular case of explosive deformation in a confined space (to each particular deformation condition) there exists a definite problem, namely, the strength problem with a subsidiary condition on the uniform compression pressure. Any restrictions on the size of the deformed charge are in most cases apparently insignificant, since the limiting sizes are fairly small. The hazard of explosive deformation in a confined space should depend both on its properties (critical stress, mechanical properties) and on the deformation conditions. Although each particular case is uniquely defined, at the same time for some cases of confined explosives a definite sensitivity series does not exist as a property of the explosive.

B. Mechanical action in an unconfined space. In such a situation there is always a zone of action of the external forces (compression zone) which is surrounded by the main explosive mass, and what determines the hazard is not only the initiation of explosion, but also the propagation of the explosive transformation from the initial hot spot to the main mass of explosive, since the latter may be damped both in the compression zone and upon emerging from it. For conditions prevailing in fall-hammer tests of solid explosives, the ignition resulting from the hot spot is damped as the pressure drops at the end of the impact or due to the ejection of some of the explosive from the compression region (the ejection may be caused by strongly compressed combustion products). In both cases burning is damped upon hydrodynamic relaxation of the compression zone. If we now assume that these factors can always operate, then for an explosive transformation to propagate continuously the burning should develop into detonation before relaxation of the compression zone. In addition, we allow for the result obtained from a study of the propagation of an explosion in thin compressed explosive layers /19, 66, 98/. If the compressed layer transforms into a noncompressed explosive, then rapid burning is damped in the transition to the noncompressed explosive and the detonation is transmitted (in this case low-velocity detonation may become normal-velocity detonation). Thus, as a basis for analyzing problems involving unconfined explosives the following fundamental processes may be considered: mechanical action; hot-spot formation in the explosive; thermal self-ignition of the hot spot; burning with transition to detonation in the compression zone; detonation in the noncompressed explosive. (Note that by using such a scheme we have in mind most secondary explosives.) If the explosive system burns so rapidly that the relaxation cannot result in damping of the burning, then the process should be modified accordingly.)

In the following we shall only analyze mechanical actions applied to an unconfined explosive. As already said, there is currently no quantitative theory for "burning with transition to detonation in the compression." It is however clear that upon emerging from the compression zone into the non-compressed explosive the conditions for the propagation of detonation (at least the critical ones) should be satisfied. Let us consider several problems of the initiation of detonation by impact using the critical conditions for the initiation of explosion in the compression zone and the critical conditions for the propagation of detonation outside the compression zone, in fact, upon

emerging from the compression zone (we assume that transition of burning into detonation in the compression zone always occurs, since only under this assumption can one at present further analyze the problem).

§3. Some general cases of mechanical action on an unconfined explosive

Impact on a half-space

We consider some models of the problem which reflect the most general form of action, and analyze the case of impact of a perfectly rigid body on a solid explosive charge. The velocity of the striker is then much lower than the velocity of sound in the exploding substance, i.e., the impact process is static. Figure 36 presents the most general schemes of mechanical action on an explosive charge. First consider Figure 36a. This layout corresponds to a problem in the theory of plasticity, in which a rigid punch with a flat base is pressed in a half-space. The two-dimensional solution is taken for simplicity (Prandtl /100/, Hill /101/, and Prager /102/ obtained some consistent solutions by the method of characteristics, the medium being idealized as a rigid-plastic body). The figure shows the glide lines after Prandtl. It follows from the solutions that the maximum hydrostatic pressure upon deformation (at the slip planes) is approximately $3\sigma_s$. This is also the magnitude of the punch pressure on the half-space. As the punch penetrates, the pressure increases until the glide lines assume the form shown in Figure 36b /103/. The pressure of the punch on the medium and the maximum uniform compression pressure on the slip planes attain the value $4.8\sigma_s$. Experimental measurements of the penetration of a cylindrical flat punch yielded a value of $\sim 3.1\sigma_s$ /58/.

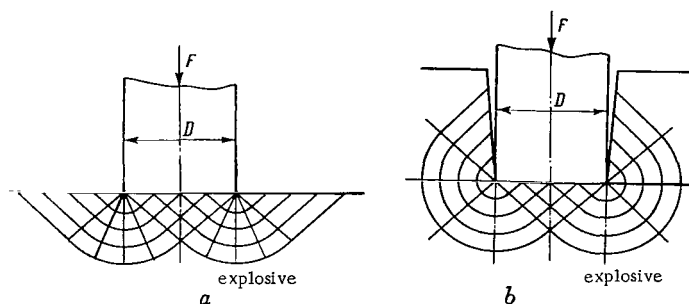


FIGURE 36. Impact on a half-space (the network of glide lines is after Prandtl):

a — no penetration; b — strong penetration.

Let us assume the solution for a rigid-plastic medium is also satisfied for brittle bodies, if the yield stress is replaced by the ultimate strength σ_{ult} (this assumption was verified experimentally for deformation in thin layers).

Since the critical stress condition limits the hydrostatic pressure to not lower than P_{cr} , in the case of impact according to Figure 36 an effective hot spot may form only for explosives obeying the relationship

$$\frac{P_{cr}}{\sigma_{ult}} \leq 3 \text{ to } 4.8. \quad (32)$$

In other words, when the strength condition for these explosives is satisfied and the impact follows the scheme under consideration, the critical stress condition is automatically satisfied. We obtained above $\bar{P}_{cr} \approx \bar{P}_{fr}$ (100%) (see Figure 33) and $P_{cr} = 1.5 - 2 \bar{P}_{cr}$. A comparison of ultimate strengths (see Table 6) and critical stresses (see Table 12) shows that for the tested initiators (or some of them) explosion can be obtained by impact on a half-space. This is an interesting experimental task, the fulfillment of which would enable condition (32) to be defined more accurately.

In order to initiate detonation of a half-space of explosive by impact, the critical conditions for the initiation of detonation should obviously be satisfied. We assume that the diameter D of the striker should be not less than the critical detonation diameter d_{cr} , and that the minimum size D_{min} of a striker which is still capable of initiating detonation should be equal to it. This yields an expression for the minimum impact force capable of initiating the detonation of a half-space of explosive:

$$\begin{aligned} F_{min} &= (3 - 4.8) \frac{\pi}{4} D_{min}^2 \sigma_{ten}, \\ D_{min} &= d_{cr}. \end{aligned} \quad (33)$$

Expressions (33) are extended to the class of explosives corresponding to relation (32). They were obtained from the mechanical failure problem and the assumption of critical detonation initiation conditions. It is however important to stress the restriction of the explosion initiation problem to small-size charges (in the case under consideration, to small dimensions of the impact zone). If this size is larger than the critical detonation diameter, then impact corresponding to the parameters given by expressions (33) does not cause detonation of the charge, since explosion is not initiated at all. The critical detonation diameters are very small for initiating explosives (for example, it is of the order of 10^{-2} mm for lead azide /104/). The model (Figure 31) used to examine the formation of localized hot spots yields some limiting sample size a_{lim} , connected with the elastic energy reserve required for creating the smallest spot capable of producing a self-propagating chemical reaction. Upon explosive deformation in instrument No. 2, the limiting charge thickness h_{lim} should be smaller than a_{lim} , owing to the large radial pressure gradient. This gradient gives rise to secondary shear and to the transformation of elastic energy (now already of uniform compression) from the maximum pressure zone into inelastic deformation work at the discontinuity surface of the rate of straining. For impact on a half-space we apply the arbitrary condition that the limiting size of the impact zone is a_{lim} (this assumption is apparently very close to reality, since the hydrostatic pressure in this case is of the same order as the ultimate strength). If $a_{lim} > d_{cr}$ the minimum size of the striker and the minimum impact force for which explosion (and subsequent detonation) should occur are given by

$$F_{\min} = (3 - 4.8) \frac{\pi}{4} D_{\min}^2 \sigma_{\text{ult}},$$

$$D_{\min} = a_{\text{lim}}. \quad (34)$$

These expressions are of value in the first place for initiating explosives. However, it is as yet impossible to make specific evaluations on the basis of these expressions. Special theoretical and experimental investigations are required in order to refine these expressions and to determine such quantities as d_{cr} and a_{lim} .

If $P_{\text{cr}} \leq \sigma_{\text{ult}}$ the critical stress condition implies that such explosives should not allow any mechanical processing, i.e., they should be supersensitive. It is interesting to note in this connection that the tested initiating explosives are not included in the supersensitive class (and this corresponds to reality: for example, when careful precautions are taken they allow mechanical grinding), since for them $P_{\text{cr}} > \sigma_{\text{ult}}$. The condition $P_{\text{cr}} \leq \sigma_{\text{ult}}$ does not exhaust the problem of explosive supersensitivity in relation to the thermal mechanism of initiation. A requirement of supersensitivity is also ease of detonation initiation; in addition, a_{lim} must be sufficiently small. Materials for which $T_{\text{cr}} \leq T_{\text{mel}}$ and $P_{\text{cr}} = 0$ should be more mechanically supersensitive. Effective hot spots can form in such materials upon dry friction of the explosive crystals with one another. Contact of foreign bodies accompanied by friction may cause the explosion of such explosives, this being easier the lower their flashpoint (rather, their critical temperature). Such considerations may explain the supersensitivity of substances like nitrogen iodide (the flash point of nitrogen iodide under a 30-sec exposure is 50°C), but the possibility that this supersensitivity is not connected with the thermal effect of mechanical action, i.e., not with heating up of the explosive upon deformation, is not excluded [11, 36].

For most secondary explosives the ratio $P_{\text{cr}}/\sigma_{\text{ult}}$ is considerably greater than 3—4.8, and in the case of impact following the scheme of Figure 36 an effective hot spot cannot form since then the critical stress condition is never satisfied owing to insufficient strength. It also follows that operations like boring and cutting of charges are not dangerous for secondary explosives (if one does not allow for heating up of the bore and the cutting instrument), since limitation of the uniform compression pressure to $3 - 4.8\sigma_{\text{ult}}$ is in any case valid also for these operations.

Impact on a thin layer

Owing to the large difference between the critical stress and the ultimate strength of most secondary explosives, it was found above that it is impossible to initiate their explosion by mechanical impact on a half-space. Since a pressure far above the tensile strength of a medium can be obtained upon deformation in thin layers, we consider another model of impact on an explosive charge (Figure 37).

Suppose a rigid flat surface supports an explosive layer, which is subject to impact by a rigid cylindrical body (of diameter D) with flat base. Figure 37a illustrates impact on a layer of high density, and Figure 37b impact on a layer of low density, for example bulk density. In the latter case, the explosive should be strongly compacted in the impact zone before a significant pressure rise begins. The deformation conditions in the impact zone are similar to the conditions in instrument No. 2 (the lateral pressure of the explosive mass surrounding the striker can be disregarded, since the explosive ultimate strength even in the cast state is very low) and were

examined above. When the critical explosion initiation conditions are satisfied, ignition takes place in the impact zone. Spreading out from the ignition spot, the explosive transformation should become detonative in order to advance beyond the compression zone. It is known that detonation can only propagate through a charge of diameter not less than d_{cr} , the critical detonation diameter (for a charge of cylindrical form). In our case the charge through which detonation should pass is a layer of thickness h ; detonation is only possible when the thickness h is not less than some critical value l_{cr} , where l_{cr} according to the meaning of the critical detonation diameter [105] is proportional to d_{cr} , i.e., for detonation to propagate beyond the impact zone it is necessary that $h \geq l_{cr} = kd_{cr}$ (k being a proportionality factor, apparently close to $1/2$). We draw attention to the fact that l_{cr} in the compression zone (a two-sided shell) is smaller than in the non-compressed layer. Thus, the propagation of detonation is limited by the noncompressed explosive, in the first place by the emergence from the compression zone into the noncompressed explosive.

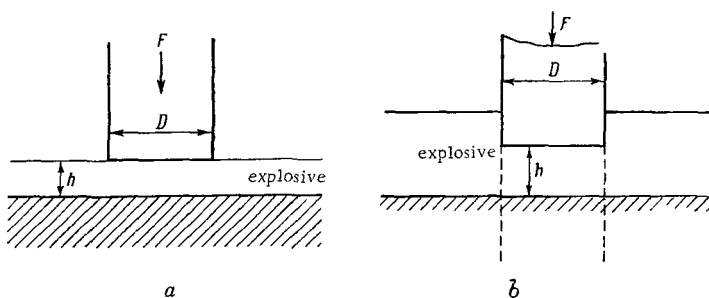


FIGURE 37. Impact on a thin layer:

a - layer density close to maximum; b - layer of low density (pressing of the material takes place at the beginning of the impact).

Now, using the critical conditions for the initiation of explosion in instrument No. 2, namely

$$\bar{P}_{ult} = \sigma_{ult} \left(1 + \frac{D}{3\sqrt{3}h} \right) = \bar{P}_{ex}, \quad (35)$$

if

$$\bar{P}_{ult} \geq \bar{P}_{cr}$$

and the necessary condition for the propagation of detonation is satisfied, i.e.,

$$h \geq l_{cr}, \quad (36)$$

we obtain expressions for the impact parameters (striker diameter D and impact force F) resulting in detonation of the whole explosive layer. If

$\bar{P}_{\text{ult}} = \bar{P}_{\text{cr}}$ and $h = l_{\text{cr}}$, then expressions (33) and (34) yield expressions for the minimum force and minimum striker diameter for which this is still possible:

$$\begin{aligned} F_{\min} &= \frac{\pi}{4} D_{\min}^2 \bar{P}_{\text{cr}}, \\ D_{\min} &= 3 \sqrt[3]{\frac{\bar{P}_{\text{cr}} - \sigma_{\text{ult}}}{\sigma_{\text{ult}}}} l_{\text{cr}}. \end{aligned} \quad (37)$$

If the diameter of the striker is less than D_{\min} or the force is less than F_{\min} , then detonation of the whole charge is impossible (provided, of course, that the velocity of the striker is much less than the velocity of sound) and explosion may occur only in the impact zone. Consider the variations which may be encountered in the case of impact on a thin layer:

1) When $h < l_{\text{cr}}$, detonation of the whole layer is impossible; explosion in the impact zone is possible if $F \geq \frac{\pi}{4} D^2 \bar{P}_{\text{cr}}$;

2) When $h \geq l_{\text{cr}}$, then for $D < D_{\min}$ detonation of the whole layer is impossible; explosion may occur only in the impact zone after one or several

attempts if $F \geq \frac{\pi}{4} D^2 \bar{P}_{\text{cr}}$ (after failures the layer thickness under the striker becomes less than l_{cr} ; at the time of failure material is ejected from the compression zone and some of the explosive surrounding the striker is scattered); for $D \geq D_{\min}$, detonation of the whole explosive layer may be initiated if $F > \frac{\pi}{4} D^2 \bar{P}_{\text{cr}} \geq F_{\min}$

Thus, for impact on a thin layer detonation can be initiated over some range of the impact parameters F and D , respectively equal to or greater than F_{\min} and D_{\min} , if the layer thickness h is equal to or greater than l_{cr} .

As for the earlier case of impact on a half-space, in the case of impact on a thin layer one should indicate the limited validity of the expressions for F_{\min} and D_{\min} associated with the critical detonation layer, when the latter is smaller than h_{lim} , the limiting thickness of the charge in instrument No. 2 for which a hot spot capable of initiating a self-propagating process of explosive transformation can still form. For $h_{\text{lim}} > l_{\text{cr}}$, the expressions for F_{\min} and D_{\min} become

$$\begin{aligned} F_{\min} &= \frac{\pi}{4} D_{\min}^2 \bar{P}_{\text{cr}}, \\ D_{\min} &= 3 \sqrt[3]{\frac{\bar{P}_{\text{cr}} - \sigma_{\text{ult}}}{\sigma_{\text{ult}}}} h_{\text{lim}}. \end{aligned} \quad (38)$$

§4. Quantitative evaluation of the sensitivity of explosives to mechanical action (Impact on an unconfined explosive)

"Minimum action" principle

While considering some general cases of mechanical actions on unconfined explosives (impact on a half-space and impact on a thin layer) the impact parameters capable of initiating detonation of the whole charge were found for each case. In each specific case the result of the impact is completely

determined by such parameters as the diameter D of the striker and the force F developing upon the impact (the impact velocity does not affect the values of D and F and the only condition required is that it should not be too large to cause the formation of a shock wave initiating detonation). It is therefore D and F on which any approach to sensitivity evaluation must be based.

Clearly, the larger the dimensions of the striker and the forces required for initiating detonation of some specific explosive, the less sensitive is this explosive to impact, i.e., the sensitivity of an explosive to impact can be put in correspondence with the quantities D_{\min} and F_{\min} . The quantities D_{\min} and F_{\min} characterize an impact upon which the conditions for initiating explosion are optimal. However, to show this or to find out more optimum conditions for explosion initiation, we further analyze the impact actions. We introduce the "minimum action" principle: of all possible conditions, the sensitivity of an explosive is characterized by the parameters of such an impact for which they are minimum. In order that the "minimum action" parameters could indeed play the role of sensitivity characteristics, they must, apart from everything else, depend only on the properties of the explosive itself and the specified parameters of state (a specified parameter of state of an explosive is, for example, the initial temperature).

Thus, according to the "minimum action" principle, explosives are compared with respect to sensitivity, not according to the parameters of action under identical conditions, but according to the parameters of action under optimum conditions for initiation of detonation in each explosive. For example, explosives for which $P_{\text{cr}} > 3 - 4.8 \sigma_{\text{ult}}$ (most secondary explosives) should not detonate upon impact on a half-space. They should also not detonate for impact on a thin layer, if the layer thickness is less than the critical l_{cr} for the propagation of detonation. Detonation can be initiated for impact on a thin layer of thickness larger than or equal to l_{cr} (we refer to the thickness of the layer compressed by the striker). It is therefore this case which should be regarded as definitive for the sensitivity of secondary explosives; in this case it should be characterized by the "minimum action" parameters.

We obtained above expressions governing F_{\min} and D_{\min} for a cylindrical striker. We show that for impact on a thin explosive layer (see Figure 37), of all configurations of a flat punch it is the cylindrical one which corresponds to the "minimum action" requirement. The mean deformation pressure of a rigid-plastic body for a rectangular punch (a and b are the sides of the rectangle) /106/ is

$$\bar{P}_s = \sigma_s \left[1 + \frac{a}{2\sqrt{3}h} \left(1 - \frac{a}{3b} \right) \right].$$

Hence it follows that the deformation force ($F = \bar{P}_s ab$) will be least for a punch of square cross section, but in this case it also exceeds by a factor of $\pi/4$ the force required in the case of a cylindrical punch. Suppose we bend the punch. The permissible tangent of the bending angle is limited (from the viewpoint of explosion initiation) to a value of the order of $(h/D)_{\text{cr}}$, which for the tested secondary explosives is small. For such small bending angles the mean deformation pressure, as shown by calculations of the sagging of wedge-like forged pieces /58/, hardly varies.

Dependence of the sensitivity of explosives to impact on its parameters of state

We consider the dependence of the "minimum action" parameters on the parameters of state of the explosive, namely, initial temperature T_0 , degree of dispersion (μ being the grain size) and density ρ . Consider first impact on a thin layer, the case covering the sensitivity of secondary explosives. Given below are expressions for D_{\min} and F_{\min} on the assumption that

$$l_{cr} = \frac{1}{2} d_{cr}:$$

$$F_{\min} = \frac{\pi}{4} D_{\min}^2 \bar{P}_{cr},$$

$$D_{\min} = 2.6 \frac{\bar{P}_{cr} - \sigma_{ult}(T_0)}{\sigma_{ult}(T_0)} d_{cr}(T_0, \mu, \rho). \quad (39)$$

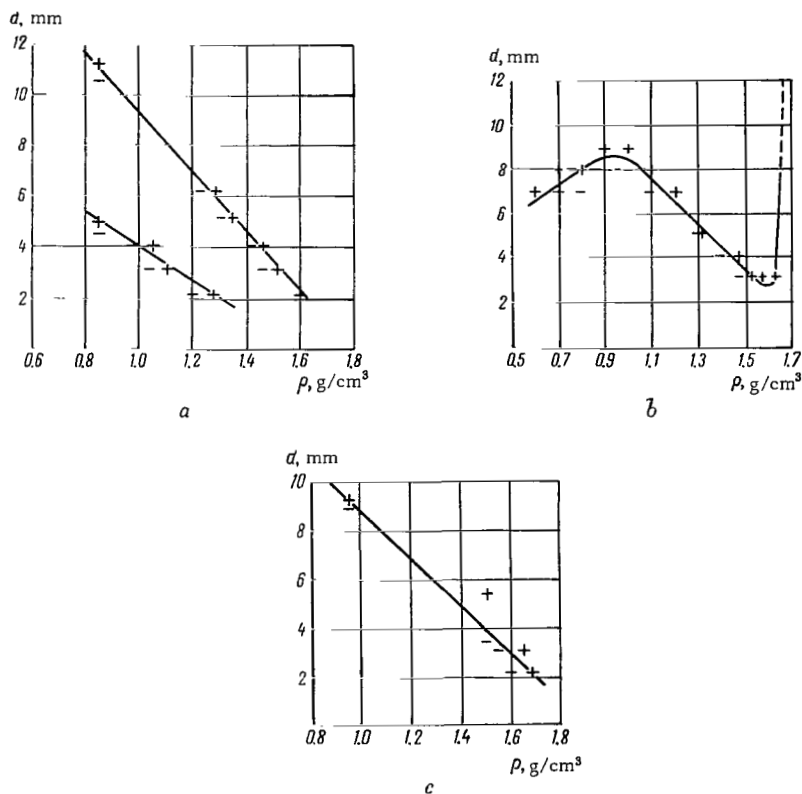


FIGURE 38. Critical detonation diameter vs. charge density:

- a – upper curve for TNT of grain size 0.07–0.2 mm; lower curve for TNT of grain size 0.01–0.05 mm (the data were obtained in a thin-walled glass casing) /107/;
- b – TNT of mean grain size 0.06 mm (cellophane casing 0.05 mm thick) /108/;
- c – trinitrophenol of grain size 0.1–0.75 mm (thin-walled glass casing) /107/.

Let us examine the dependence of these quantities on the parameters of state of the explosive. The temperature and degree of dispersion are fixed parameters of state of the explosive, whereas the density under practical conditions may vary. The influence of the density on F_{\min} and D_{\min} showed up through the density-dependence of the critical detonation diameter.

Figure 38 presents data obtained in /107–109/, which show the variations in the critical detonation diameter of chemically homogeneous secondary explosives with changing density. The critical diameter is seen to decrease with increasing density and, passing through a minimum, sharply increases near the single-crystal density. In accordance with the "minimum action" principle, D_{\min} and F_{\min} correspond to the density for which the critical detonation diameter is least (this value is denoted by $d_{\text{cr min}}$, and the critical thickness of the layer for which detonation is possible by $l_{\text{cr min}}$). For evaluating the sensitivity of secondary explosives to impact we therefore obtain

$$\begin{aligned}(F_{\min})_{\text{abs}} &= \pi/4 (D_{\min})_{\text{abs}}^2 \bar{P}_{\text{cr}}, \\ (D_{\min})_{\text{abs}} &= 3 \sqrt{3} \frac{\bar{P}_{\text{cr}} - \sigma_{\text{ult}}(T_0)}{\sigma_{\text{ult}}(T_0)} l_{\text{cr min}}(T_0, \mu) \cong \\ &\cong 2.6 \frac{\bar{P}_{\text{cr}} - \sigma_{\text{ult}}(T_0)}{\sigma_{\text{ult}}(T_0)} d_{\text{cr min}}(T_0, \mu).\end{aligned}\quad (40)$$

We turn now to the dependence of the sensitivity of secondary explosives to impact on the degree of dispersion and the initial temperature. According

to /40/, the effect of the degree of dispersion of an explosive on its sensitivity causes only a variation in the critical detonation diameter, which decreases with decreasing grain size /110–112/. Figure 39 presents data for the dependence of the critical detonation diameter, obtained in /112/ for bulk density for a number of explosives. The decrease in critical diameter with decreasing grain size also occurs for charges pressed to high densities (see Figure 38). A rise in initial temperature results in a decrease in the ultimate strength (see Figure 16) and in the critical detonation diameter. The decrease in critical diameter with increasing temperature is illustrated by Figure 40, which is based on data obtained (for TNT) in /113/ (the degree of dispersion of the powdery TNT used in this work is not given). According to expression (40), the effect of the initial temperature on $(D_{\min})_{\text{abs}}$ and $(F_{\min})_{\text{abs}}$ may be different: as the temperature varies over different ranges, the sensitivity of explosives may both rise and fall.

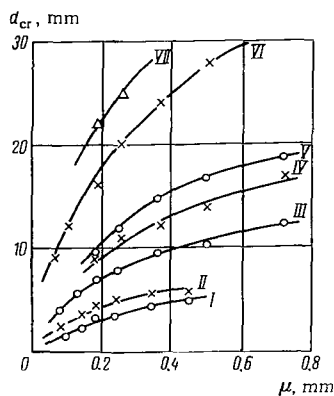


FIGURE 39. Critical detonation diameter vs. grain size (cellophane casing 0.05 mm thick; density of charges 1.0 g/cm³) /112/:

I – PETN; II – RDX; III – Tetryl; IV – trinitrophenol; V – TNT with crystalline grain; VI – TNT with aggregated grain; VII – TNT + 1% paraffin oil.

Consider now impact on a half-space. As regards the effect of density, this scheme already assumes a highly compacted state of the charge. If the charge has maximum density (the density of a single crystal), then

$$F_{\min} = (3 - 4.8) \frac{\pi}{4} (D_{\min}^0)^2 \sigma_{\text{ult}}(T_0),$$

$$D_{\min}^0 = d_{\text{cr}}^0(T_0), \quad (41)$$

where d_{cr}^0 is the critical detonation diameter for single-crystal density.

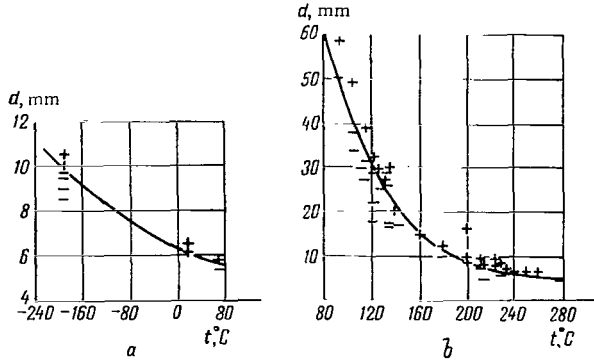


FIGURE 40. Critical detonation diameter of powdery (a) and molten (b) TNT vs. initial temperature (glass casing) /113/.

The "minimum action" principle corresponds to a density for which the critical detonation diameter is smallest. We denote the minimum impact parameters corresponding to $d_{\text{cr min}}$ by $(D_{\min})_{\text{abs}}$ and $(F_{\min})_{\text{abs}}$. Let us examine the dependence of these parameters on the degree of dispersion of the explosive and on the initial temperature. The critical detonation diameter depends on the degree of dispersion and therefore when $d_{\text{cr}} \geq a_{\text{lim}}$ the "minimum action" parameters which can initiate detonation are

$$(F_{\min})_{\text{abs}} = (3 - 4.8) \frac{\pi}{4} D_{\min}^2 \sigma_{\text{ult}},$$

$$(D_{\min})_{\text{abs}} = d_{\text{cr min}}(\mu).$$

It should be noted that the condition $d_{\text{cr min}}(\mu) > a_{\text{lim}}$ is itself dependent on the degree of dispersion. We show also that the critical detonation diameter and, consequently, $(D_{\min})_{\text{abs}}$ depend on the grain size as long as the latter is not larger than the critical detonation diameter of the explosive for the single-crystal density, d_{cr}^0 , when the minimum diameter and impact force are determined by (41). This is important, in particular for initiating explosives, the possibility of initiating their detonation by impact on a half-space having been discussed above. The critical detonation diameters for single-crystal density in the case of such explosives are small and the range of dependence of $(D_{\min})_{\text{abs}}$ and $(F_{\min})_{\text{abs}}$ on the degree of dispersion is apparently very narrow.

It is of interest to follow the effect of the initial temperature upon detonation by impact on a half-space. First, the condition (32) itself of initiating explosion by impact on a half-space depends on the temperature:

$$\frac{P_{cr}}{\sigma_{ult}(T_0)} \leq 3 \text{ to } 4.8 \quad (42)$$

and as the initial temperature of the explosive rises it may no longer be possible to initiate detonation. Further, if condition (42) is satisfied, the values of $(D_{min})_{abs}$ and $(F_{min})_{abs}$ are found from expressions (33) or (34), depending on whether the critical diameter is greater or smaller than a_{lim} . However, both the critical detonation diameter and a_{lim} are themselves dependent on the temperature; $d_{cr}^0(T_0)$ and $d_{cr min}(T_0, \mu)$ decrease with increasing temperature, and a_{lim} depends on it according to (27) as follows:

$$a_{lim} = \frac{2JE(T_0) \rho r_{lim}(T_0)}{\sigma_{ult}(T_0)} [c(T_{cr} - T_0) + L]. \quad (43)$$

If

$$d_{cr}^0(T_0) > d_{cr min}(T_0, \mu) > a_{lim}(T_0),$$

then parameters $(D_{min})_{abs}$ and $(F_{min})_{abs}$ in accordance with

$$(F_{min})_{abs} = (3 - 4.8) \frac{\pi}{4} (D_{min})_{abs}^2 \sigma_{ult}(T_0)$$

and

$$(D_{min})_{abs} = d_{cr min}(T_0, \mu) \quad (44)$$

decrease with increasing temperature. If $a_{lim}(T_0) > d_{cr}^0(T_0) > d_{cr min}(T_0, \mu)$, then their dependence on the initial temperature takes the form

$$(F_{min})_{abs} = (3 - 4.8) \frac{\pi}{4} (D_{min})_{abs}^2 \sigma_{ult}(T_0),$$

$$(D_{min})_{abs} = a_{lim}(T_0); \quad (45)$$

for $\mu \geq d_{cr}^0(T_0) > a_{lim}(T_0)$ the minimum diameter and impact force decrease with increasing temperature according to (41).

As for impact on a half-space, one can also study impact on a thin layer and analyze the influence of the initial temperature on the "minimum action" parameters as dependent on the relationships $l_{cr min}(T_0, \mu)$ and $h_{lim}(T_0)$. If $l_{cr min}(T_0, \mu) > h_{lim}(T_0)$, then this influence is characterized by expressions (40). If $h_{lim}(T_0) > l_{cr min}(T_0, \mu)$, then

$$(F_{min})_{abs} = \frac{\pi}{4} (D_{min})_{abs}^2 \bar{P}_{cr},$$

$$(D_{min})_{abs} = 3 \sqrt{3} \frac{\bar{P}_{cr} - \sigma_{ult}(T_0)}{\sigma_{ult}(T_0)} h_{lim}(T_0). \quad (46)$$

The relation $h_{lim}(T_0)$ and the quantities determining it are unknown. However, if the condition $h_{lim}(T_0) > l_{cr min}(T_0, \mu)$ is satisfied, then $(D_{min})_{abs}$ and $(F_{min})_{abs}$ are independent of the degree of dispersion of the explosive, though this condition itself is dependent on it. The same also refers to the range $\mu \geq l_{cr}^0(T_0) > h_{lim}(T_0)$ which remained the only one not considered: $l_{cr}^0(T_0)$ is the critical thickness of a layer capable of detonation as a function of the initial

temperature. Over this range

$$F_{\min}^0 = \frac{\pi}{4} (D_{\min}^0)^2 \bar{P}_{\text{cr}},$$

$$D_{\min}^0 = 3 \sqrt{3} \frac{\bar{P}_{\text{cr}} - \sigma_{\text{ten}}(T_0)}{\sigma_{\text{ten}}(T_0)} l_{\text{cr}}^0(T_0). \quad (47)$$

Evaluation of the sensitivity of explosives to mechanical action

The above expressions for the minimum impact parameters as a function of the parameters of state of the explosive apparently exhaust the principal cases of impact on an unconfined explosive. According to the "minimum action" principle, the sensitivity of an explosive for definite parameters of state (degree of dispersion and initial temperature) should be evaluated from the minimum values of the indicated impact parameters, i.e., the sensitivity should be determined by that case which leads most easily to the initiation of detonation of the whole charge. Consider now the possibility of generalizing the obtained estimates, at present applicable only to impact, to general mechanical action on an unconfined explosive. For this purpose, information on the behavior of explosives obtained in experiments with slow loading of charges onto a press, and the "minimum action" principle understood in a broad sense, will be used.

If the quantities entering the expressions for $(D_{\min})_{\text{abs}}$ and $(F_{\min})_{\text{abs}}$ in the cases of impact and slow loading were identical, the values of $(D_{\min})_{\text{abs}}$ and $(F_{\min})_{\text{abs}}$ would not depend upon the rate of the external action. Nevertheless, it is the case of impact which would characterize the sensitivity of an unconfined explosive to mechanical action, since the force necessary to initiate detonation would be attained in this case much more easily owing to the small action time of the force. In this connection the value itself of $(F_{\min})_{\text{abs}}$ is also important, since forces of, say, hundreds of kilograms applied statically are in general hardly encountered in the practical handling of explosives (we refer to unconfined explosives), whereas in the case of impact, forces of, say, tens of tons can develop due to a load of 10 kg falling from a height of 25 cm. Thus, the forces upon impact and upon static loading are far from equivalent from the point of view of their practical realizability. To some extent this is reflected by the quantity $F_{\min} \tau_{\text{act}}$ (τ_{act} being the time of action of the force), which in the case of impact is the momentum of the striker. If, however, the minimum force $(F_{\min}^{\text{st}})_{\text{abs}}$ required for initiating detonation of a statically loaded charge is 100 kg, and the minimum force $(F_{\min})_{\text{abs}}$ required for initiating detonation by impact exceeds it even by an order, then apparently there are no doubts that the hazard of some specific unconfined explosive is characterized by the impact case.

Quantities such as the critical detonation diameter and critical stress involved in the expressions for $(D_{\min})_{\text{abs}}$ and $(F_{\min})_{\text{abs}}$ are independent of the rate of application of the load. The rate of straining only affects the tensile strength under conditions of fairly high pressures. Pressure has a plasticizing effect, and when the rate of straining is low, plastic deformation accompanied by consolidation develops, which results in a higher tensile strength. When the pressure is removed, the consolidation effect is also

removed. If the pressures under which deformations occur are fairly small, then the explosives behave brittly also for small rates of straining. For example, when loaded by a press in instrument No. 2, charges with a ratio h/D exceeding 0.10 as a rule fracture brittly when the average pressure attains a value corresponding to the strength curve upon impact. It follows from the inequality $h/D > 0.1$, the relation $P_{cr} = (1.5 - 2) \bar{P}_{cr}$ and the strength condition that the effect of the rate at which the action is applied should be insignificant for explosives obeying $P_{cr}/\sigma_{ult} < 4.5 - 6$. The initiating explosives which were tested satisfy this condition. Upon slow loading of thin layers with $h/D \leq 0.1$, the mechanical properties of the explosives change as compared with the case of impact loading. The result of these changes is expressed by the fact that in the case of slow deformation of thin layers, the charge thickness for which explosions occur exceeds by not more than a factor of 2 or 3 the value of h_{cr}^{II} obtained for impact (instrument No. 2). Since $h_{cr}^{II} \sim \sigma_{ult}/(\bar{P}_{cr} - \sigma_{ult})$, it follows from expressions (40) that $(F_{min})_{abs}/(F_{min}^{st})_{abs} < 10$.

Thus, the sensitivity of an unconfined explosive to mechanical action is determined (in practice) by the sensitivity to impact for those explosives whose $(F_{min})_{abs}$, obtained from measurements upon impact, is at least not less than 10^3 kg. Substances for which $(F_{min})_{abs}$ is less than 10^3 kg have a high sensitivity to mechanical action. Their sensitivity apparently is higher than that of PETN of grain size 100μ at normal temperature (numerical estimates will be given below). If the value of $(F_{min})_{abs}$ obtained from impact tests is less than 10^3 kg, then with decreasing $(F_{min})_{abs}$ along with a large increase in sensitivity to impact, the explosives become increasingly more sensitive to static loading. For example, crushing initiating explosives in a mortar becomes extremely hazardous, apart from the hazard of impacts. The quantity $(F_{min})_{abs}$ obtained from impact measurements should preserve its value as an index of relative sensitivity to static mechanical action also for substances which occupy an intermediate position with respect to sensitivity between PETN and initiating explosives, if this value maintains its correlation with the analogous value found for slow loading. Thus, the above estimates of the sensitivity of explosives to impact fairly well represent within wide limits the sensitivity of the explosives to static (slow) action. They can probably be used with greater justification for the combined case of both impact and slow loading, i.e., to characterize the sensitivity of (unconfined) explosives to mechanical action.

The sensitivity of explosives, estimated from $(D_{min})_{abs}$ and $(F_{min})_{abs}$, depends only on the properties of the explosives (strength, melting temperature, thermochemical and kinetic properties, detonation capability, etc.). The sensitivity of an explosive increases with higher detonation capability and the more capable it is of reaction. The obviousness of this relationship bears out the correction of the proposed estimates. The influence of the parameters of state of an explosive on its sensitivity to mechanical action is expressed by the dependence of the sensitivity-determining properties on these parameters. The dependence (40) of the sensitivity of an explosive on the degree of dispersion agrees with a fact, known from handling practice, that an explosive used in the form of large grains is less sensitive. Highly dangerous are explosives in a highly dispersed state (accidental aggregations of explosive dust may cause a serious accident during production).

Applicability limits of the obtained sensitivity estimates

Consider now the limits of applicability of the expressions obtained for the "minimum action" parameters. We turn first to the impact velocity. The impact velocity should not be so large that a shock wave initiating detonation will form in the charge. Thus, the velocity of the incident body for which detonation of the charge is initiated by a shock wave must be estimated. Suppose the impact occurs according to the scheme shown in Figure 30a. For impact by a colliding body of velocity u_0 , the interface of the explosive with this body moves with velocity u_2 . For shock waves of sufficiently small amplitude we have (the acoustic approximation)

$$\frac{u_0 - u_2}{u_2} = \frac{\rho_{\text{ex}} c_{\text{ex}}}{\rho_b c_b}, \quad (48)$$

where ρ_b and c_b are the density and velocity of sound for the material of the incident body; ρ_{ex} and c_{ex} are the same for the explosive charge.

It follows from formula (48) that the larger the acoustic stiffness of the incident body, the higher the mass velocity u_2 in the shock wave propagating through the charge, for the same impact velocity u_0 . If, for example, the incident body is made of steel, then for secondary explosives the mass velocity u_2 is close to the impact velocity even for a charge of single-crystal density ($\rho_{\text{ex}} c_{\text{ex}} / \rho_b c_b \approx 0.1$). Since we are interested in the lowest impact velocities for which a shock wave initiates detonation, we will consider in the following the case when the acoustic stiffness of the incident body is high, and consequently $u_2 \approx u_0$. Detonation initiation by a shock wave is a complicated process depending on the pressure in the shock wave, its form and duration, as well as on the transverse dimensions of the incident body. At present only an approximate allowance for these factors is possible. To initiate detonation, the diameter of the striker should be equal to the critical detonation diameter (and then the velocity of the initiating shock wave should be equal to the detonation velocities under critical conditions [114]) or larger than it (in which case the velocity of the initiating shock wave decreases with increasing diameter and for $D \gg d_{\text{id}}$ it approaches the velocity of sound [115]; d_{id} is the approximate value of the smallest charge diameter for which the detonation velocity equals the ideal for the given density). The decrease in the velocity of the initiating shock wave and in its amplitude with increasing diameter is due to the weakening of the lateral hydrodynamic unloading. The duration of the shock wave effect is determined by the longitudinal dimension l of the striker, on which the axial unloading depends. When the longitudinal size of the striker decreases, the pressure in the shock wave, necessary for initiating detonation, increases. If $l \geq c_b d_{\text{id}} / 2c_{\text{ex}}$, then the axial unloading becomes insignificant and the critical pressure in the initiating wave does not vary [115].

Thus, the critical pressure in the initiating shock wave should be least for $l \geq c_b d_{\text{id}} / 2c_{\text{ex}}$ and $D \gg d_{\text{id}}$. We will assume that the dimensions of the incident body satisfy these conditions. The critical pressure of the initiating shock wave depends strongly on the density. For example, in the case of TNT for a density variation from 1.0 to 1.63 g/cm³, according to the data of various authors it varies from 8 or 9 to 130–150 kbar [118]. To estimate

the lowest impact velocity which initiates detonation due to a shock wave, we refer to bulk densities. The lowest published critical pressures in the shock wave amount to 2.5—3 kbar (highly dispersed PETN /116/ and oktogen /117/). Using the generalized shock adiabat for porous organic materials /118/, we obtain for the required u_0 a value of approximately 500 m/sec. In general, for each explosive there exists its lowest impact velocity for which detonation is initiated by a shock wave (this value depends upon the degree of dispersion and the initial temperature). If we assume that the range of mechanical action refers to impact velocities below 10^2 m/sec, then this apparently will satisfy all the explosives used.

Consider further how the "minimum action" parameters change as the initial temperature rises and approaches the melting temperature. From (40), (43), (45), and (46) it follows that as one approaches the melting temperature ($\sigma_{ul} \rightarrow 0$), the values of a_{lim} , $(D_{min})_{abs}$, and $(E_{min})_{abs}$ tend to infinity and thereby the explosives as though become absolutely insensitive (it is clear that for explosives which flash before the onset of melting, the tending of the ultimate strength to zero can only be of formal importance). In reality, this means that near the melting temperature the ideas of the hot spot mechanism, developed for solids, become inapplicable. As already said when analyzing the mechanical properties of explosives, as one approaches melting temperatures, the plasticity of the explosive increases and, apparently, transition to models of relaxing media are required: first of a viscoplastic body, and then of a viscous fluid. Accordingly, one should expect transition to other mechanisms of explosion initiation upon mechanical action.

Apparently, this transition occurs when $T_0/T_{mel} \approx 0.9$ (it was pointed out above that the annealing of the rollers upon the explosion of dina, whose corresponding temperature in normal conditions is 0.9, is similar to that which occurs for ballistites in the zone of viscoplastic deformation). The value $T_0/T_{mel} \approx 0.9$ can be regarded as an approximate applicability limit of the proposed sensitivity estimates.

It is of interest to note that if the initiation of explosion were determined not by the deformation of the charge as a whole, but were the result of microdisplacements in the charge, then also in that case the obtained values of $(D_{min})_{abs}$ and $(F_{min})_{abs}$ would preserve their significance as "minimum action" parameters capable of initiating detonation of the whole charge.

Methods of determining the quantities which characterize sensitivity

The problem of the initiation of explosion and the critical conditions of detonation propagation was applied above to obtain expressions for estimating the sensitivity of unconfined explosives to mechanical action. These expressions were derived without quantitative allowance for the development of the explosion from the initial hot spot to detonation, but on the assumption that burning always transforms into detonation in the compression zone. Therefore, the expressions for the "minimum action" parameters, corresponding to which a definite mechanical sensitivity (for an unconfined explosive) is taken

as a property of the explosive, may prove to be incomplete. Having mentioned this limitation, we consider further the proposed sensitivity estimates and results arising from them.

The quantities $(D_{\min})_{\text{abs}}$ and $(F_{\min})_{\text{abs}}$ are functions of the explosive properties determining the sensitivity, and so depend on such parameters of state as the degree of dispersion and initial temperature of the explosive. It is therefore possible to speak of a definite mechanical sensitivity of an explosive only for a given degree of dispersion and initial temperature.

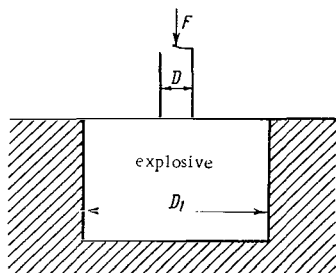


FIGURE 41. Test scheme for simulating impact on a half-space.

Consider the experimental methods for determining the parameters of "minimum action" which can initiate detonation of a whole charge. Figure 41 shows a test scheme for finding $(D_{\min})_{\text{abs}}$ and $(F_{\min})_{\text{abs}}$ in the case of impact on a half-space. In this case the charge diameter D_1 should be at least 6 times as large as the striker diameter D (a further increase in D_1 does not affect the force developed by the punch /58/). For the same reason, the charge height for a striker stroke equal to $2D$ should be not less than $4D$. A striker stroke of $2D$ is quite sufficient to

develop the maximum penetration force (see Figure 36b). As already mentioned, the scheme of impact on a half-space itself assumes a highly compacted state of the charge. Therefore, practical tests according to this scheme should be carried out, but for different densities fairly close to the single-crystal density (the density for which the critical detonation diameter is least). The test scheme for impact on a thin layer is shown in Figure 37a. For powerful explosives $(D_{\min})_{\text{abs}}$ corresponds to high densities, since the critical detonation diameter assumes the least value for a pressed charge density approaching the single-critical density (see Figure 38).

For weak explosives (ammonium nitrate, ammonium perchlorate) and their mixtures with fuel, the critical detonation diameter increases with increasing density (Figure 42) and the smallest value occurs for a low density /110, 119/. Therefore low densities correspond to the quantity $(D_{\min})_{\text{abs}}$ in which case one should apparently consider the bulk (gravimetric) density. The intermediate case, when the critical detonation diameter first increases and then decreases with increasing density, is observed for "ammotol 50/50" (Figure 43) /120/. A similar dependence of the critical diameter on density is observed for TNT over the range of very low densities (see Figure 38b).

Thus, different densities should correspond to the quantity $(D_{\min})_{\text{abs}}$ for different explosives. A direct method of finding $(D_{\min})_{\text{abs}}$ for impact on a thin layer consists in dropping loads with strikers of different diameters onto explosive layers of various thicknesses and densities. Since impact on a thin layer should cause explosion in all explosives, and impact on a half-space should cause explosion only in those explosives satisfying condition (32), it is therefore expedient first to find $(D_{\min})_{\text{abs}}$ for impact on a thin layer (the impact energy in this case may be arbitrarily large) and then check whether the impact of a load with a striker of such a diameter initiates

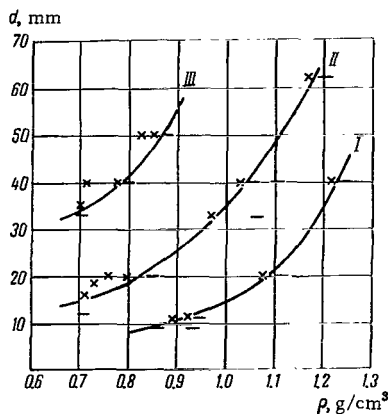


FIGURE 42. Critical detonation diameter of "dinamon" vs. density (glass casing) /110/:

I – fine grinding ($\mu < 0.1$ mm); II – medium grinding; III – coarse grinding ($\mu = 0.2 - 0.4$ mm).

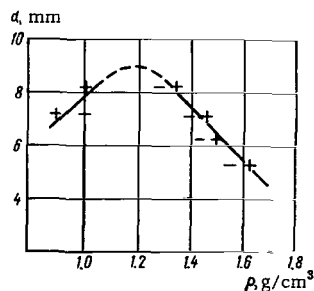


FIGURE 43. Critical detonation diameter of "ammotol 50/50" vs. density (thin-walled glass casing, $\mu \approx 0.4$ mm) /120/.

detonation of the charge in a test simulating impact on a half-space (see Figure 41). If the latter does not occur, then the value of $(D_{\min})_{\text{abs}}$ found for impact on a thin layer is the required value. If in tests according to Figure 41 the charge detonates, then, by reducing the striker diameter, one should arrive at a diameter for which detonation does not occur, and thereby determine the required value of $(D_{\min})_{\text{abs}}$. Then, retaining the same conditions under which $(D_{\min})_{\text{abs}}$ was determined, one can measure the minimum impact force $(F_{\min})_{\text{abs}}$.

The above expressions for $(D_{\min})_{\text{abs}}$ and $(F_{\min})_{\text{abs}}$ had the shortcoming that they did not allow quantitatively for detonation formation phenomena in the compression zone. The described method of measuring these quantities is free of this shortcoming (as well as of the assumptions made in the derivation of the estimates) and is in this sense ideal. Indeed, the experimental determination of the parameters of "minimum action" which initiate detonation of a whole charge, alone already allows for the transition of burning into detonation, the transmission of detonation to the noncompressed explosive, etc. (detonation can proceed both with normal and with low velocities: from the hazard point of view, no distinction is made between these conditions). The described comprehensive method is, however, difficult in practice, requires proving-ground conditions for most explosives, and a large amount of work.

We introduce various simplifications, which to some extent result in the loss of the advantages of the direct method. Since $(F_{\min})_{\text{abs}}$ is proportional to $(D_{\min})_{\text{abs}}^2$, it is almost always possible for estimating sensitivity to use one of these quantities, for example $(D_{\min})_{\text{abs}}$, which is more common. With the aid of condition (32), one can also indicate approximately the explosives which should explode upon impact on a half-space. Using the empirical relation $\sigma_{\text{ult}} = 4.2 T_{\text{mel}}$, formula (1) and condition (32) yield

$$T_{\text{cr}} \leq 1.4 T_{\text{mel}} \quad (49)$$

where T_{cr} and T_{mel} are given in degrees Celsius. This condition apparently should be satisfied by most nonmelting explosives (deflagration before the onset of melting). Most explosives, however, whose melting temperature is below the flash point should be tested only according to the scheme of impact on a thin layer. A separate determination of $l_{cr\ min}$ results in a further simplification. (The determination of this quantity, if small, may prove technically to be a complicated problem.) If the value of $l_{cr\ min}$ is known in advance, then by subjecting to impact at once a layer of such thickness, one easily finds $(D_{min})_{abs}$. Those explosives which satisfy condition (49) should be tested similarly, but the quantity $(D_{min})_{abs}$ should then, as in the direct method, be checked by the half-space impact scheme.

We turn now to computational methods of determining quantities characterizing the sensitivity of explosives to mechanical action. The above expressions for these quantities were obtained correct to the transition of burning to detonation in the compression zone. To calculate $(D_{min})_{abs}$ and $(F_{min})_{abs}$ such quantities as P_{cr} , \bar{P}_{cr} , σ_{ult} , $l_{cr\ min}$, $d_{cr\ min}$, l_{cr}^0 , d_{cr}^0 , a_{lim} , and h_{lim} must be known. Then, depending on the relationship between $l_{cr\ min}$, h_{lim} , l_{cr}^0 , and μ for impact on a thin layer or $d_{cr\ min}$, a_{lim} , d_{cr}^0 , and μ for impact on a half-space, one should use the corresponding expressions obtained above for each particular case. However, it is practically impossible to calculate the indicated quantities, since either the necessary data or a quantitative theory is missing. For example, the critical stress can be calculated only approximately; earlier only rough estimates were made. Application of the relationship between ultimate strength and melting temperature is also possible only within certain limits, owing to its empirical character. All these quantities must therefore at present be determined experimentally. If one uses experimental data, the method becomes semicomputational. Relation (32), or its approximate analog (49), allows one to easily determine the possibility of initiating explosion by the half-space impact scheme, or the thin-layer impact scheme. For example, most secondary explosives should explode only for impact on a thin layer. The critical detonation diameter d_{cr}^0 for single-crystal density in the case of secondary explosives usually far exceeds the commonly used grain sizes (Table 14).

TABLE 14. Characteristics of a number of common explosives

Explosive	$\sigma_{ult}, \frac{kg}{cm^2}$	$\bar{P}_{cr} \cdot 10^{-3}, kg/cm^2$	$(h/D)_{cr} \cdot 10^{-2}$	d_{cr}, mm	D_{min}, cm	F_{min}, kg	d_{cr}^0, mm	D_{min}^0, cm
TNT	340	~11	~0.8	12	~75	~5.3 · 10 ⁷	~70	440
Trinitrophenol	520	9.5	~1.1	7	~32	8.9 · 10 ⁶	—	—
Tetryl	520	~8.4	~1.2	5	19	~2.4 · 10 ⁶	—	—
RDX	820	7.0	2.5	2.5	5.0	1.3 · 10 ⁵	7.0	14
Oktogen	1250	6.4	4.3	4	4.6	1.1 · 10 ⁵	18	20
PETN	600	4.8	2.7	2	3.7	4.8 · 10 ⁴	5.0	9.3
Lead azide	1550	2.6	28	—	—	—	10 ⁻²	10 ⁻³

As was tentatively indicated above, the value of h for secondary explosives amounts to hundredths of a millimeter, which apparently is much smaller than $l_{cr\ min}$ and $d_{cr\ min}$ if the material is not very finely ground. Hence it

follows that $(D_{\min})_{\text{abs}}$ and $(F_{\min})_{\text{abs}}$ should be found from expressions (40). However, the required data on $l_{\text{cr min}}$ (as well as on $d_{\text{cr min}}$) for various explosives do not exist.

The dependence of the critical detonation diameter on density has been studied in more or less detail for TNT of average grain size 0.06 mm (Figure 38b). In this case the smallest value of the critical diameter is approximately 2 mm. From expressions (40) for TNT ($\bar{P}_{\text{cr}} \approx 11,000 \text{ kg/cm}^2$, $\sigma_{\text{ult}} = 340 \text{ kg/cm}^2$) of such a grain size we have $(D_{\min})_{\text{abs}} \approx 12.5 \text{ cm}$ and $(F_{\min})_{\text{abs}} \approx 1.5 \cdot 10^6 \text{ kg}$. Note that the results given in Figure 38 refer to normal-velocity detonation. The propagation of detonation with low or normal velocity should not be distinguished from the hazard point of view. The critical conditions of detonation propagation at low velocity were studied only for bulk density /121/. A low-velocity detonation has not been observed by anyone for highly compacted charges without a casing, and apparently it should not exist. For powerful explosives one may therefore expect the smallest critical diameter to correspond to normal-velocity detonation. The critical diameter of low-velocity detonation may be necessary, for example, for ammonium nitrate explosives, the detonation capability of which decreases with increasing density. The dependence of detonation velocity on charge diameter was measured for some industrial explosives in /122/.

Since we cannot calculate $(D_{\min})_{\text{abs}}$ and $(F_{\min})_{\text{abs}}$ for different explosives, we try to compare them with respect to sensitivity, using the results for the critical detonation diameters in the case of bulk density. Table 14 presents data on the detonation capability of various explosives at normal temperature, bulk density (1.0 g/cm^3) and degree of dispersion ($\mu = 0.1 \text{ mm}$) close to the technological values (see Figure 39), as well as for single-crystal density /109/. (The data for oktogen were obtained by Apin and Velina.) In addition, the table presents also measured values of the ultimate stress σ_{ult} , the critical stress in instrument No. 2, $(h/D)_{\text{cr}}$, values of D_{\min} and F_{\min} calculated from expressions (39) for bulk density, as well as values of D_{\min} for single-crystal density. The value of D_{\min} follows directly from the value of $(h/D)_{\text{cr}}$:

$$D_{\min} = \frac{d_{\text{cr}}}{2 (h/D)_{\text{cr}}}.$$

The values obtained for D_{\min} and F_{\min} greatly exceed $(D_{\min})_{\text{abs}}$ and $(F_{\min})_{\text{abs}}$, which characterize the sensitivity of explosives to mechanical action.

If, in particular, the values of D_{\min} and F_{\min} are calculated for TNT of bulk density with an average grain size of 0.06 mm, they are found to be respectively a factor of ~ 6 and ~ 36 times as small as the values of $(D_{\min})_{\text{abs}}$ and $(F_{\min})_{\text{abs}}$ given above for TNT of the same grain size. For PETN, as expected, this difference is even smaller, since in this case the smallest critical detonation diameter ($\mu = 0.1 \text{ mm}$) should be 0.3 mm, which is only 3 times as large as the grain size and is hardly possible. However, for such a difference too, the value of $(F_{\min})_{\text{abs}}$ would be not less than 10^3 kg , a value which we used when discussing the applicability of quantitative estimates of the sensitivity of explosives to impact, to mechanical action (on an unconfined explosive) in general. The sensitivity of initiating explosives should be much higher than that of PETN, since they detonate when tested according to [the scheme of] Weller, i.e., $(D_{\min})_{\text{abs}}$ for these explosives is below 1.5 mm. The values of D_{\min}^0 , calculated for lead azide in the half-space and thin-layer

impact schemes, are of the order of 10^{-2} mm. Since the values of a_{lim} and h_{lim} remain unknown, these values may be underestimated with respect to $(D_{\text{min}})_{\text{abs}}$.

If we use the computed values of D_{min} and F_{min} (see Table 14) as approximate sensitivity indices, the investigated explosives can be arranged in the following series (of increasing sensitivity): TNT, trinitrophenol, Tetryl, RDX, oktogen, PETN, initiating explosives. This series of sensitivity of explosives to mechanical action is the same as the reference series. It should be noted that a comparison of explosives with respect to sensitivity for some other, but uniform degree of dispersion would not introduce changes in this series, since the only quantity depending on it (the critical detonation diameter) changes similarly for the tested secondary explosives when the grain size is varied, i.e., the ratio of the critical diameters for different explosives and various grain sizes is preserved (see Figure 42).

In expression (40) for $(D_{\text{min}})_{\text{abs}}$ (proposed for a quantitative evaluation of the sensitivity of secondary explosives), the factor $(\bar{P}_{\text{cr}} - \sigma_{\text{ult}})/\sigma_{\text{ult}}$ represents the initiation of explosion and the factor $l_{\text{cr min}}$ (or $d_{\text{cr min}}$) the propagation of detonation (it being assumed that transition of burning into detonation always occurs in the compression zone). This by no means implies that one may consider separately the sensitivity of an explosive to initiation of explosion and the sensitivity to propagation of detonation. Only a joint consideration of the two enables one to speak of the mechanical sensitivity of an explosive. If we tried to estimate the relative sensitivity of an explosive to initiation of explosion from the quantity $(\bar{P}_{\text{cr}} - \sigma_{\text{ult}})/\sigma_{\text{ult}}$, in reality we would be evaluating the sensitivity of the explosive to mechanical action on the assumption that $l_{\text{cr min}}$ (or in general the capacity of the explosive to propagate explosion) is identical for comparable substances. (This assumption was made when considering the deformation of a confined explosive; in this case the hazard evaluation reduces to the problem of the initiation of explosion, since the propagation of explosion for a confined explosive should then follow spontaneously.) In exactly the same way, if $l_{\text{cr min}}$ is assumed to characterize the sensitivity to explosion propagation, we would evaluate the sensitivity of the explosive to mechanical action as though the other factor [in (40)] is constant for comparable substances. Although examples of this kind yield information on the sensitivity, we considered the two factors under discussion for another purpose. The factor representing the initiation of explosion was determined accurately, whereas the factor representing the propagation is based on a number of assumptions. In addition, we replaced the factor $l_{\text{cr min}}$ when calculating D_{min} and F_{min} (see Table 14) by the quantity $1/2 d_{\text{cr}}$ for the bulk density. Taking into account the form of the relationship between critical detonation diameter and density (see Figure 38), it can be assumed that the explosive series with respect to critical diameter does not change with increasing density. Since the series of all tested explosives (except oktogen) both with respect to the first and to the second factor remained unaltered, the sensitivity series obtained from $(D_{\text{min}})_{\text{abs}}$ and $(F_{\text{min}})_{\text{abs}}$ will be the same as that obtained above. It can also be expected that the relative difference in $l_{\text{cr min}}$ and $d_{\text{cr min}}$ will be smaller than the difference in the critical values for bulk density, so that the part played by the factor accounting in the estimate for the initiation of explosion will increase considerably. This may result in oktogen being even closer to PETN (or even exceeding it) from the point of view of sensitivity.

Sometimes, for example in the synthesis of explosives, a rapid, though rough estimate of the sensitivity of some new material is required. In a very rough approximation such a method is suitable for individual explosives. From relation (3), used earlier for rough estimates of the critical stress P_{cr} , it follows that $P_{cr} \sim T_{cr} - T_{mel}$. In turn, $T_{cr} - T_{mel}$ increases with increasing difference between the flash point and the melting temperature. Using in addition the empirical relation $\sigma_{ult} = 4.2 T_{mel}$ and the inequality $\bar{P}_{cr} \geq \sigma_{ult}$ (which is usually well satisfied for secondary explosives), expression (40) yields the following relationship for a rough comparison of the sensitivity of an explosive:

$$(D_{min})_{abs} \sim \frac{T_{fl} - T_{mel}}{T_{mel}} /_{cr \min} \quad (50)$$

where T_{fl} and T_{mel} are expressed in degrees Celsius.

A tentative idea of the sensitivity of any given explosive can be obtained by comparing it with a sensitivity reference series. If the value of $(T_{fl} - T_{mel}) / T_{mel}$ for the given explosive approximates that for one in the reference series, then the question as to which of them is more sensitive depends on the detonation capability. For secondary explosives, the latter is as a rule higher the stronger the explosive. This approach works for a number of simple cases. However, if in this way oktogen is compared with PETN or RDX, it is impossible in this complicated case to reach any definite conclusion. The use of this tentative method may sometimes lead to errors, for example in the case of dina, which does not fit the empirical dependence of the tensile strength on the melting temperature. Nonetheless, such errors are very rare and this method may often be useful for a preliminary tentative evaluation of the sensitivity of new explosives, especially as a large amount of material is not required. (In the experimental synthesis of an explosive, such quantities as T_{mel} and T_{fl} are usually determined also for other purposes.) This method, although leaving much to be desired as regards accuracy, is nevertheless more rigorous than comparing the frequency of explosions in a standard instrument or in instrument No. 2 which, from the point of view of sensitivity evaluation, is unreliable.

In our study of mechanical action applied to an unconfined explosive, we showed in particular the possibility of applying the idea of a definite sensitivity to mechanical action as a property of each explosive, as well as the possibility of a quantitative expression for this property. Since the expressions for $(D_{min})_{abs}$ and $(F_{min})_{abs}$ were obtained without any quantitative allowance for the explosion growth from the initial hot spot to detonation, they should be improved. However, even in this form these estimates reflect fairly well the ideas of the relative sensitivity (reference series) of explosives and the dependence of the sensitivity on various factors. The latter can be illustrated by studying possible ways of desensitizing explosives.

§5. Desensitization of explosives

The high sensitivity of explosives to mechanical action is often the main obstacle to their production and use. Artificial lowering of the sensitivity of explosives (desensitization) is therefore particularly important.

Possible methods of desensitization follow quite readily from an analysis of the obtained quantitative sensitivity estimates. For this purpose we express $(D_{\min})_{\text{abs}}$ and $(F_{\min})_{\text{abs}}$ approximately in the simplest form, using the proportionality between the tensile stress and the melting temperature and the successive proportionality

$$\begin{aligned}\bar{P}_{\text{cr}} &\sim P_{\text{cr}} \sim T_{\text{cr}} - T_{\text{mel}}, \\ (F_{\min})_{\text{abs}} &\sim (D_{\min})_{\text{abs}}^2 (T_{\text{cr}} - T_{\text{mel}}), \\ (D_{\min})_{\text{abs}} &\sim \frac{T_{\text{cr}} - T_{\text{mel}}}{T_{\text{mel}}} l_{\text{cr min}}.\end{aligned}\quad (51)$$

An increase in $(D_{\min})_{\text{abs}}$ and $(F_{\min})_{\text{abs}}$ should correspond to a lowering of sensitivity. It hence follows that the sensitivity of an unconfined explosive to mechanical action can be lowered by increasing $l_{\text{cr min}}$, increasing T_{cr} , and decreasing T_{mel} .

The method of lowering sensitivity by reducing the melting temperature can be realized by preparing eutectic explosive alloys. This method is very simple and should have a fairly strong effect, since T_{mel} is involved both in the numerator and in the denominator of expressions (51). The sensitivity of the eutectic should decrease relative to at least one of the individual explosives forming the eutectic. Even greater sensitization can be achieved by creating ternary eutectic alloys (or with an even larger number of components).

Another desensitization method is to increase the critical detonation diameter. For this one could increase the grain size in technological products, if the grain size is smaller than the critical detonation diameter of a single crystal.

Yet another method follows from expressions (40), and consists in lowering the tensile stress of the explosive using surface-active materials, by introducing into the explosive low-strength or low-viscosity additives, etc. The introduction of such additives also increases the critical detonation diameter, giving an additional desensitization effect. As additives one can choose low-strength and low-sensitivity explosives, as well as low-strength and low-viscosity materials, which improve the oxygen balance of the principal explosive, so helping to raise the strength of the composition. This desensitization method is widely used in practice (the alloys TNT + RDX, RDX + a paraffin-type additive, plastic explosives, water-soaked explosives). It should be noted that inert plasticizing additives considerably hamper the development of explosion from the initial hot spot to detonation /93, 123/, a stage of the process which is not allowed for in the proposed estimates. In practice, plasticizing additives are even used for desensitizing initiating explosives.

Thus, the proposed sensitivity estimates somewhat substantiate desensitization methods widely used in practice (which in turn confirm the estimates themselves) and reveal some new methods. The estimates show the possibility of a quantitative approach to explosive desensitization which until now has been carried out empirically.

Conclusions

The above-formulated problem of initiation of explosion by mechanical action and the currently available qualitative information on the growth of explosion from a localized hot spot allowed us to examine the principles of a quantitative approach to sensitivity problems, to define more accurately the concept of sensitivity, and to propose a simple sensitivity estimate for action on an unconfined explosive.

Suppose we classify mechanical action into two classes: deformation of a confined explosive and action on an unconfined explosive. These classes differ from the point of view of a quantitative estimate of their danger. In the case of deformation of a confined explosive (pressing, screwing, ammunition equipment, etc.) localized ignition is followed by a spontaneous process of explosion growth, and an evaluation of the hazard of such a deformation reduces to the problem of explosion initiation. Since this solution in each specific case depends both on the properties of the explosive and on the deformation conditions, whatever form the deformation takes in the case of a confined explosive, no such property as a specific explosive sensitivity exists. In the case of mechanical action on an unconfined explosive, only a detonation process can emerge beyond the limits of the compression zone and propagate throughout the main mass of the explosive, since burning is attenuated under hydrodynamic loading, for example (as shown by observations), upon emergence from the compression zone. The hazard of such an action (i.e., the sensitivity to it) is therefore determined both by the initiation of explosion in the compression zone, and by the latter beyond the compression zone. Thus, in the case of deformation of a confined explosive, the concept of sensitivity to mechanical action as the capacity of an explosive to explode under such an action is valid. In the case of an unconfined explosive, it requires concrete definition: sensitivity is the capacity of an explosive to detonate under these actions (this definition does not cover the explosion only in the compression zone). However, if we speak of explosion of the **whole** charge, then the concept becomes common for both cases of mechanical action.

Suppose we separate those mechanical effects on an unconfined explosive to which the given explosive is sensitive. It is natural then to determine the sensitivity of this substance to the weakest action. In other words (the "minimum action" principle) the sensitivity to mechanical action of an unconfined explosive should be characterized by that weakest effect, when the conditions of initiation and growth of explosion as well as of the propagation of detonation for this explosive are satisfied, i.e., such an action which optimizes initiation of charge detonation. This was the guiding principle in the derivation of quantitative estimates of the sensitivity of an unconfined explosive to impact. It was used to select the optimum (from the viewpoint of detonation initiation) impact scheme (on a half-space or a thin layer), the shape of the striker and the density of the explosive. Evaluation of explosive sensitivity is made subject to the smallest values of the striker diameter and the force upon impact, for which detonation of the main mass of explosive can still be initiated. Quantitative expressions for these quantities are based on the critical conditions for initiation of explosion and the critical conditions for detonation propagation. All the expressions were obtained on the assumption that, if these conditions are satisfied, detonation

always forms in the compression zone (there are currently no theoretical models which could be used to describe the growth of explosion from a hot spot to detonation). The "minimum action" principle made it possible to substantiate that estimates of explosive sensitivity to impact to a large extent also reflect the general sensitivity of the explosive to mechanical action (in the case of an unconfined explosive). The obtained estimates are inapplicable to impact speeds which are so high that detonation would be initiated by the shock wave produced by the impact. They are also inapplicable at initial temperatures close to the melting temperature of the explosive, since when approaching the liquid state, the mechanism responsible for initiation of explosion in solids is no longer important.

According to the obtained estimates, the sensitivity of an unconfined explosive to mechanical action is higher, the higher the reactivity of the explosive, its strength, melting temperature, and detonation capability. These properties can be modified by desensitization of the explosive. The influence of the initial temperature and degree of dispersion of the explosive on the sensitivity is revealed through their dependence on the critical detonation diameter and the dependence of the strength on the initial temperature. An approximate calculation of the sensitivity of unconfined explosives to mechanical action at normal temperature and for a degree of dispersion close to technological yields a series of explosive sensitivities which agrees with the reference series.

This, as shown in §1 of the Introduction, is a necessary condition for the method of estimating sensitivity to be correct. An independent confirmation of the estimates also follows from their consistency with the generally used methods of explosive desensitization.

Thus, the division of all mechanical actions into two classes enabled us to resolve the inconsistency regarding the question of the existence of such a property of explosives as a specific mechanical sensitivity: it exists for an unconfined explosive but does not exist in the case of deformation of a confined explosive. Our attempt at a quantitative approach to sensitivity problems should be regarded only as an initial stage of the development of a sensitivity theory (a discussion of the principles of the treatment).

CONCLUSION

Let us indicate briefly the directions in which future research in the field of the sensitivity of explosives (solid explosives, pyrotechnic compositions, solid rocket propellants, ballistites, liquid explosives) to mechanical action might be undertaken. A separate examination of deformation of a confined explosive and of mechanical action on an unconfined explosive apparently remains expedient for all explosive systems. In addition, in the case of deformation of a confined explosive, no such characteristic of an explosive system as a specific mechanical sensitivity exists and it will be necessary to investigate the initiation of explosion in every case. For an experimental study of the sensitivity of explosive systems to deformation of a confined quantity, modeling methods will apparently play the principal role. Mechanical action on an unconfined explosive, in addition to the problem of initiation of explosion for all explosive systems, involves quantitative allowance for the explosion propagation conditions and corresponding refinement of the sensitivity concept. In this case, it will apparently be possible to speak of such a characteristic of an explosive system as a specific mechanical sensitivity, for a quantitative expression of which the use and improvement of the principle of "minimum action" will be required. Thus, when developing a theory of sensitivity of various explosive systems, the general methodological approach can be expected to be the same each time; in particular, a knowledge of the quantitative regularities of the initiation and propagation of the explosion will be necessary. A classification of mechanical actions can further be detailed, thereby reflecting the specific peculiarities of the production and use of the various explosive systems. We note also that desensitization methods suitable for an unconfined explosive are not necessarily suitable for some specific case of deformation of a confined explosive, and may sometimes yield opposite results.

Consider now solid explosives. As regards deformation of a confined explosive, they require investigation of a number of particular problems of explosion initiation, on the basis of which a theory of pressing safety, a theory of premature explosion of bursting projectiles upon shooting, etc., could be worked out. As regards action on an unconfined explosive, all studies are to some extent connected with a quantitative evaluation of sensitivity: either they serve to improve sensitivity or to derive relationships between sensitivity and some specific factors. The latter is required for analyzing the influence of the parameters of state of the explosive (initial temperature, degree of dispersion, humidity) on the sensitivity, for choosing desensitization measures and for clarifying the relation between sensitivity and the chemical composition of the explosive. The clarification of this relationship is of great importance for the synthesis of explosives.

Its derivation assumes the existence of at least dependences of reactive capacity, strength, melting temperature, and detonation capacity on the structure, each of which is still far from having been determined and form separate fundamental investigations. Nevertheless, existing trends in the variation of melting temperature, flash point, and strength of explosives, say within some homologous series or when substitutes are introduced, may often be a useful, though approximate guide for selecting the sort of synthesis. The dependence of sensitivity on composition has been touched upon and is based on data regarding the percentages of explosions in specific instruments /1, 69, etc./; however such studies are of very limited interest here.

To improve estimates of the sensitivity of unconfined solid explosives to mechanical action, a theory of the heating mechanism and an investigation into the mechanics of failure and its typical accompanying processes are required. A study is required of the causes of the spread in the mechanical strength of charges, because it is this phenomenon which introduces a probabilistic character in the testing of explosives. Observations of the width of the probability zone and the establishment of a unique experiment are of fundamental importance as a direct proof of the nonstatistical approach to the phenomenon of explosion initiation, used in the theory. Whereas a theoretical study of the heating mechanism and the process of mechanical failure enables one to derive an analytic expression of the quantities already involved in the estimate, the investigation of the critical conditions for explosion growth can lead to the incorporation of new physical quantities. Improvement of estimates will therefore be mainly determined by investigation of explosion growth. In deriving the estimates we considered only the case of a normal detonation formed in the compression zone. If, however, detonation propagates in the compression zone with low velocity, then the density of the explosive in the noncompressed zone should obviously be fairly low for the transition of detonation into the noncompressed explosive. The critical thickness of the compressed layer may then considerably exceed the value of $l_{cr\ min}$, used above. In other cases it is necessary to take into account the length of the section required for the growth of explosion from the hot spot to detonation. These processes, as already said, do not have a quantitative theory. It is, however, significant that for an experimental estimate of sensitivity such a theory is not needed, since in any case one has to determine the smallest value of the striker diameter yielding detonation of the whole charge. The problem of a method of testing the sensitivity of solid explosives should therefore be regarded as solved in principle; only the difficulties associated with its most convenient technical interpretation remain.

Consider briefly the relative character of sensitivity evaluation, namely, that it is possible only to speak of a higher or lower sensitivity of one explosive as compared with another. It would be meaningless, for example, to say that the sensitivity of some explosive is so many times higher than that of another explosive. No single sensitivity has this property: in this sense it is analogous with such a property of explosives as, for example, detonation capacity. It is most convenient to compare explosives with respect to sensitivity, against those explosives about whose sensitivity fairly firm empirical ideas exist, e.g., the explosives of a reference series.

Thus the reference series, agreement with which served earlier as a necessary condition for the validity of an estimate, now acquires a no less important role, namely, that of an empirical "sensitivity scale."

In conclusion we note that in practice explosive mixtures are mostly used. The initiation mechanism of explosive mixtures has a number of peculiarities which are still in the initial stage of study. Such a study should result in rules for the preparation of mixtures, ensuring that they have an acceptable sensitivity to mechanical action.

Considerable difficulties are also encountered in the investigation of the mechanism of initiation of explosion of ballistic powders, pyrotechnical compositions, and solid rocket propellants. The diverse mechanical properties of these systems imply a diversity in the forms of their explosion initiation mechanism. In this connection, an important role may be attributed to the physicochemical interaction of the components. The heating mechanism as a result of external friction will probably be important in these systems. A fairly important role in the case of friction may belong to electrical phenomena, which hitherto have been ignored in connection with sensitivity problems. For ballistic powders, pyrotechnical compositions and solid rocket propellants (as opposed to explosives), the principal regime of explosive transformation is burning. Thus, the sensitivity of these systems to mechanical action in the case of an unconfined quantity should be understood as their capability of burning as a result of mechanical actions. Among the parameters of mechanical action determining sensitivity, the rate of action should be important. This particularly refers to systems containing polymers. The problem of the existence of such a property as a specific sensitivity can only be solved after determining all the action parameters determining the initiation and propagation of burning.

Bibliography

1. Baum, F.A., K.P. Stanyukovich, and B.I. Shekhter. Fizika vzryva (Physics of Explosion). — Moskva, Fizmatgiz. 1959.
2. Kholevo, N.A. — In: Sbornik "Fizika vzryva," No. 3, p. 16. Moskva, Izdatel'stvo AN SSSR. 1955; In: Sbornik "Teoriya vzryvchatykh veshchestv," p. 5. Moskva, Oborongiz. 1963.
3. Kholevo, N.A. — Trudy Kazanskogo khimiko-tehnologicheskogo instituta, No. 10: 91. 1946; No. 11: 116. 1947.
4. Andreev, K.K. — In: Sbornik "Teoriya vzryvchatykh veshchestv," p. 37. Moskva, Oborongiz. 1963.
5. Andreev, K.K. — Ibid., p. 89.
6. Andreev, K.K. and Yu.A. Terebilina. — Ibid., p. 53.
7. Kistiakovski, G.B. and R. Connor. — Science in World War II, v. Chemistry. 1946.
8. Koenen, H., K.M. Ide, and W. Haupt. — Explosivstoffe, 6(8): 178. 1958.
9. Ryabinin, Yu.N. — ZhFKh, Vol. 20: 1363. 1946.
10. Ryabinin, Yu.N. — Doklady AN SSSR, Vol. 58: 245. 1947.
11. Bowden, F.P. and A.D. Yoffe. Fast Reactions in Solids. — London, Butterworths. 1958.
12. Bridgman, P.W. — J. Chem. Phys., Vol. 15: 311. 1947.
13. Khariton, Yu.B. — In: Sbornik po teorii vzryvchatykh veshchestv, p. 177. Moskva, Oborongiz. 1940.
14. Belyaev, A.F. — Ibid., p. 7.
15. Garner, W.E. — Trans. Faraday Soc., Vol. 34(985): 1008. 1938.
16. Muraour, H. — Ibid., p. 989.
17. Author's Certificate [Patent] 158727; Byull. izobret., No. 22: 53. 1963.
18. Bowden, F.P. — In: Proc. Ninth Intern. Symp. Combustion, p. 499, New York — London, Academic Press. 1963.
19. Bowden, F.P. and A.D. Yoffe. Initiation and Growth of Explosion in Liquids and Solids. — Cambridge University Press. 1952.
20. Bolkhovitinov, L.G. — Doklady AN SSSR, Vol. 126: 3220. 1959.
21. Gordeev, V.E., A.I. Serbinov, and Ya.K. Troshin. — PMTF, No. 1: 45. 1967.
22. Bowden, F.P. and M.P. McOnie. — Nature, Vol. 206: 380. 1965.
23. Rideal, E.K. and A.J. Robertson. — Proc. Roy. Soc., Vol. A195: 135. 1948.
24. Prager, W. — In: Sbornik "Mekhanika," No. 5(51), p. 121. Moskva. 1958.
25. Birger, I.A. — Izvestiya AN SSSR, Mekhanika i Mashinostroenie, No. 1: 193. 1964.

26. Freidental', A. and Kh. Geiringer. Matematicheskie teorii neuprugoi sploshnoi sredy (Mathematical Theories of Nonelastic Continuous Media). — Moskva, Fizmatgiz. 1962.
27. Sukhikh, V. A. and Yu. B. Khariton. — In: Sbornik "Voprosy teorii vzryvchatykh veshchestv," No. 1: 149. Moskva — Leningrad, Izdatel'stvo AN SSSR. 1947.
28. Bowden, F. P. and D. Tabor. Friction and Lubrication. — Wiley. 1957.
29. Bolkhovitinov, L. G. — Doklady AN SSSR, Vol. 125: 570. 1959.
30. Bolkhovitinov, L. G. — ZhFKh, Vol. 34: 476. 1960.
31. Bolkhovitinov, L. G. Candidate Thesis. — Moskva, IKhF AN SSSR. 1960.
32. Bridgman, P. W. — J. Chem. Phys., Vol. 9: 794. 1941.
33. Leitman, Ya. I. — In: Sbornik "Voprosy teorii vzryvchatykh veshchestv," No. 1: 134. Moskva — Leningrad, Izdatel'stvo AN SSSR. 1947.
34. Wenograd, J. — Trans. Faraday Soc., Vol. 57: 1612. 1961.
35. Chaiken, R. F. and F. I. Cheselske. — J. Chem. Phys., Vol. 43: 3228. 1965.
36. Andreev, K. K. and A. F. Belyaev. Teoriya vzryvchatykh veshchestv (Theory of Explosives). — Moskva, Oborongiz. 1963.
37. Bolkhovitinov, L. G. and P. F. Pokhil. — Doklady AN SSSR, Vol. 123: 637. 1958.
38. Bobolev, V. K. and L. G. Bolkhovitinov. — Izvestiya AN SSSR, OKhN, No. 4: 754. 1960.
39. Afanas'ev, G. T., V. K. Bobolev, and L. G. Bolkhovitinov. — Doklady AN SSSR, Vol. 136: 642. 1961.
40. Semenov, N. N. O nekotorykh problemakh khimicheskoi kinetiki i reaktsionnoi sposobnosti (On Some Problems of Chemical Kinetics and Reactivity). — Moskva, Izdatel'stvo AN SSSR. 1958.
41. Frank-Kamenetskii, D. A. Diffusion and Heat Exchange in Chemical Kinetics. — Princeton Univ. Press. 1955.
42. Todes, O. U. — ZhFKh, Vol. 13: 868. 1939.
43. Rice, O. K. — J. Am. Chem. Soc., 57(310): 1044, 2212. 1935.
44. Goheen, H. E. — J. Math. Phys., Vol. 20: 107. 1949.
45. Boddington, T. — Proc. Ninth Intern. Symp. Combustion, p. 287. New York — London, Academic Press. 1963.
46. Friedman, M. H. — Trans. Faraday Soc., Vol. 59: 1865. 1963.
47. Zinn, J. — J. Chem. Phys., Vol. 36: 1949. 1962.
48. Merzhanov, A. G., V. V. Barzykin, and V. M. Gontkovskaya. — Doklady AN SSSR, Vol. 148: 380. 1963.
49. Thomas, P. H. — Combustion and Flame, Vol. 9: 369. 1965.
50. Merzhanov, A. G. — Combustion and Flame, Vol. 10: 341. 1966.
51. Merzhanov, A. G. — Moskva, IKhF AN SSSR. 1959.
52. Robertson, A. J. B. — Trans. Faraday Soc., Vol. 44: 977. 1948.
53. Andreev, K. K. Termicheskoe razlozhenie i gorenje vzryvchatykh veshchestv (Thermal Decomposition and Burning of Explosives). — Moskva, "Nauka," 1966.
54. Serbinov, A. I. — Doklady AN SSSR, Vol. 129: 627. 1959.
55. Ol'shak, V., Ya. Rykhlevskii, and V. Urbanovskii. Teoriya plastichnosti neodnorodnykh sred (Theory of Plasticity of Inhomogeneous Media). — Moskva, "Mir." 1964.

56. Orlova, E. Yu. Khimiya i tekhnologiya brizantnykh vzryvchatykh veshchestv (Chemistry and Technology of High Explosives). — Moskva, Oborongiz. 1960.
57. Gubkin, S. I., B. P. Zvorono, V. F. Katkov, I. A. Noritsyn, E. A. Popov, G. A. Smirnov-Alyayev, A. D. Tomlenov, E. P. Unksov, and L. A. Shofman. Osnovy teorii obrabotki metallov davleniem (Principles of the Theory of Metal Working by Pressure). — Moskva, Mashgiz. 1959.
58. Unksov, E. P. Inzhenernaya teoriya plastichnosti (Engineering Theory of Plasticity). — Moskva, Mashgiz. 1959.
59. Bakshi, O. A. and L. M. Kachanov. — Izvestiya AN SSSR. Mekhanika, No. 2: 134. 1965.
60. Sokolovskii, V. V. Teoriya plastichnosti (Theory of Plasticity). — Moskva, GITTL. 1950.
61. Ljungberg, S. — Nobel Hefte, Vol. 1: 40. 1958.
62. Kil'chevskii, N. A. Teoriya soudareniya tverdykh tel (Theory of Collision of Solids). — Moskva — Leningrad, Gostekhizdat. 1949.
63. Dinnik, A. N. — Izbrannye trudy, Vol. 1, Kiev, Izdatel'stvo AN USSR. 1952.
64. Afanas'ev, G. T. and V. K. Bobolev. — Doklady AN SSSR, Vol. 138: 886. 1961.
65. Kobeko, P. P. Amorfnye veshchestva (Amorphous Substances). — Moskva — Leningrad, Izdatel'stvo AN SSSR. 1962.
66. Afanas'ev, G. T., V. K. Bobolev, A. V. Dubovik, and V. S. Zhuchenko. — In: Sbornik "Vzryvnoe delo," No. 63/20. Moskva, "Nedra," p. 86. 1967.
67. Andreev, K. K. and Yu. A. Terebilina. — In: Sbornik "Teoriya vzryvchatykh veshchestv," p. 72. Moskva, Oborongiz. 1963.
68. Taylor, W. and A. Weale. — Proc. Roy. Soc., Vol. A138: 92. 1932.
69. Weller, L. and O. Wencelberg. — In: Sbornik "Initsiiruyushchie veshchestva," Issue 2, p. 97, Moskva — Leningrad, ONTI. 1935.
70. Urbanski, T. — Sprengstoffes, Vol. 2: 41. 1938; Vol. 3: 62. 1938.
71. Vasil'ev, M. Ya., D. B. Balashov, and L. N. Mokrousov. — ZhFKh, Vol. 34: 2454. 1960.
72. Bochvar, A. A. Metallovedenie (Physical Metallurgy). — Moskva, Metallurgizdat. 1956.
73. Afanas'ev, G. T., V. K. Bobolev, I. A. Karpuchin. — In: Sbornik "Vzryvnoe delo," No. 52/9, p. 5. Moskva, Gosgortekhzdat. 1963.
74. Tarnovskii, I. Ya., A. A. Pozdeev, O. A. Ganago, V. L. Kolmogorov, V. N. Trubin, R. A. Vaisburd, and V. I. Tarnovskii. Teoriya obrabotki metallov davleniem (Theory of Metal Working by Pressure). — Moskva, Metallurgizdat. 1963.
75. Zener, C. and L. H. Hollomon. — J. Appl. Phys., Vol. 15: 22. 1944.
76. Yakutovich, M. V. and F. P. Rybalko. — Doklady AN SSSR, Vol. 60: 227. 1948.
77. Thomas, T. V. Plastic Flow and Fracture in Solids. — Academic Press. 1961.
78. Kachanov, L. M. Osnovy teorii plastichnosti (Principles of the Theory of Plasticity). — Moskva, GITTL. 1956.
79. Hill, R. — In: Sbornik "Mekhanika," No. 3(49) p. 53, Moskva. 1958.

80. Hill, R. — In: Sbornik "Mekhanika," No. 1 (47), p. 77. — Moskva. 1958.
81. Koiter, W. T. Obshchie teoremy uprugoplasticheskikh sred (General Theorems of Elastoplastic Media). — Moskva. 1961.
82. Berenblatt, G. I. — PMTF, No. 4: 3. 1961.
83. Deryagin, B. V. Chto takoe trenie (What Friction Is). — Moskva, Izdatel'stvo AN SSSR. 1963.
84. Pashkov, P. O. Razryv metallov (Rupture of Metals). — Leningrad, Sudpromgiz. 1960.
85. Pashkov, P. O. — PMTF, No. 6: 182. 1963.
86. Vavilov, A. F. and V. P. Voinov. Svarka treniem (Friction Welding). — Moskva, Mashinostroyeniye. 1964.
87. Vill', V. I. Svarka metallov treniem (Friction Welding of Metals). — Moskva, Mashgiz. 1959.
88. Malmrud, S. and S. Claesson. — Ark. Kemi, Vol. 25: 201. 1965.
89. Bridgman, P. W. Noveishie raboty v oblasti vysokikh davlenii (Latest Works in the Field of High Pressure). — Moskva. 1948.
90. Hill, R. — In: Sbornik "Mekhanika," No. 1 (47), p. 77, Moskva. 1958.
91. Andreev, K. K., N. D. Maurina, and Yu. A. Rusakova. — Doklady AN SSSR, Vol. 105: 533. 1955.
92. Andreev, K. K. and Yu. A. Terebilina. — In: Sbornik "Teoriya vzryvchatykh veshchestv," p. 81. Moskva, Oborongiz. 1963.
93. Bobolev, V. K. and I. A. Karpukhin. — FGV, No. 4: 471. 1967.
94. Johansson, C. H., A. Person, and H. L. Selberg. — Appl. Sci. Res., Vol. A5: 439. 1955.
95. Ogibalov, P. M. and I. A. Kiiko. Povedeniye veshchestv pod davleniem (Behavior of Matter Under Pressure). — Moskva, Izdatel'stvo MGU. 1962.
96. Feldmann, H. D. Cold Forging of Steel. — Hutchinson. 1961.
97. Belyaev, A. F., V. K. Bobolev, and Z. I. Ratner. — Doklady AN SSSR, Vol. 50: 303. 1945.
98. Bobolev, V. K. and A. V. Dubovik. — PMTF, No. 2: 150. 1965.
99. Dubovik, A. V. and V. K. Bobolev. — In: Sbornik "Vzryvnoye delo," No. 63/20, "Nedra," p. 72. Moskva. 1967.
100. Sbornik "Teoriya plastichnosti." — Moskva. 1948.
101. Hill, R. The Mathematical Theory of Plasticity. — Oxford, Clarendon Press. 1950.
102. Prager, W. and P. G. Hodge. The Theory of Perfectly Plastic Solids. — New York, Wiley. 1951.
103. Tomlenov, A. D. Teoriya plasticheskikh deformatsii metallov (Theory of Plastic Deformation of Metals). — Moskva, Mashgiz. 1951.
104. Belyaev, A. F., L. I. Azbukina, and L. N. Stesik. — In: Sbornik "Fizika vzryva," No. 3: 135, Moskva, Izdatel'stvo AN SSSR. 1955.
105. Khariton, Yu. B. — In: Sbornik "Voprosy teorii vzryvchatykh veshchestv," No. 1: 7. Moskva—Leningrad, Izdatel'stvo AN SSSR. 1947.
106. Meyerhof, G. G. and T. K. Chaplin. — Brit. J. Appl. Phys., Vol. 4: 20. 1953.
107. Bobolev, V. K. — Doklady AN SSSR, Vol. 57: 789. 1947.
108. Stesik, L. N. and L. N. Akimova. — ZhFKh, Vol. 33: 1762. 1959.

109. Apin, A. Ya. and N. F. Velina. — In: Sbornik "Vzryvnoe delo," No. 63/20, "Nedra," p. 5, Moskva. 1967.
110. Belyaev, A. F. — In: Sbornik "Voprosy teorii vzryvchatykh veshchestv," No. 1: 29, Moskva, Izdatel'stvo AN SSSR. 1947.
111. Bobolev, V. K. — In: Sbornik "Fizika vzryva," No. 2: 167, Moskva, Izdatel'stvo AN SSSR. 1953.
112. Apin, A. Ya. and L. N. Stesik. — In: Sbornik "Fizika vzryva," No. 3: 87, Moskva, Izdatel'stvo AN SSSR. 1955.
113. Belyaev, A. F. and R. Kh. Kurbangalina. — ZhFKh, Vol. 34: 603. 1960.
114. Rempel', G. G. — In: Sbornik "Teoriya vzryvchatykh veshchestv," p. 561, Moskva, Oborongiz. 1963.
115. Baum, F. A. and A. S. Derzhavets. — In: Sbornik "Vzryvnoe delo," No. 60/17; "Nedra," p. 68, Moskva. 1966.
116. Seay, G. E. and L. B. Seely. — J. Appl. Phys., Vol. 32: 1092. 1961.
117. Dubovik, A. V. Candidate Thesis. — Moskva, IKhF AN SSSR. 1966.
118. Voskoboynikov, I. M., A. I. Afanasenkov, and V. M. Bogomolov. — FGV, No. 4: 585. 1967.
119. Gor'kov, V. A. and R. Kh. Kurbangalina. — FGV, No. 2: 21. 1966.
120. Bobolev, V. K. Candidate Thesis. — Moskva, IKhF AN SSSR. 1947.
121. Parfenov, A. K. and A. Ya. Apin. — Nauchno-tekhnicheskie problemy goreniya i vzryva, No. 1: 109. 1965.
122. Parfenov, A. K., I. M. Voskoboynikov, and A. Ya. Apin. — In: Sbornik "Vzryvnoe delo," No. 60/17, "Nedra," p. 29, Moskva. 1966.
123. Linder, P. W. — Trans. Faraday Soc., Vol. 53: 1024. 1961.

National Aeronautics and Space Administration

WASHINGTON, D. C. 20546

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

OFFICIAL BUSINESS

05U 001 58 51 3DS 71088 00903
AIR FORCE WEAPONS LABORATORY /WLOL/
KIRTLAND AFB, NEW MEXICO 87117

ATT E. LOU BOWMAN, CHIEF, TECH. LIBRARY